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Transport of Dredged Sediment Placed in the Nearshore Zone - Currituck Sand-Bypass Study (Phase I)

by
Robert K. Schwartz and Frank R. Musialowski

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New dredge-disposal techniques may serve the dual role of aiding sand bypassing across coastal inlets, and beach nourishment, provided the dredged sediments placed seaward of the surf zone move shoreward into that zone. During the summer of 1976, 26,750 cubic meters of relatively coarse sediment was dredged from New River Inlet, North Carolina, moved downcoast by a split-hull barge, and placed in a 215-meter coastal reach between the 2- and 4-meter depth contours. Bathymetric changes on the disposal piles and in the adjacent beach and nearshore area were studied for a 13-week period (August to November 1976) to determine the

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modification of the surrounding beach and nearshore profile, and the net transport direction of the disposal sediment.

The sediment piles initially created a local shoal zone with minimum depths of 0.6 meter. Disposal sediment was coarser (Mn = 0.49 millimeter) than the native sand at the disposal site (Mn = 0.14 millimeter) and coarser than the composite mean grain size of the entire profile (Mn = 0.21 millimeter). Shoaling and breaking waves caused rapid erosion of the pile tops and a gradual coalescing of the piles to form a disposal bar located seaward (≈ 90 meters) of a naturally occurring surf zone bar. As the disposal bar relief was reduced, the disposal bar-associated breaker zone was restricted to low tide times or periods of high wave conditions.

The disposal bar eventually migrated landward, in some cases at a rate between 2.5 and 4.5 meters per day, although movement appeared sporadic and to coincide most directly with periods of increased wave activity. With development of the disposal bar, the inner surf zone bar was displaced landward. Sediment, some similar in appearance to disposal sediment, filled the inshore surf zone trough located landward of the surf zone bar. The trough downdrift from the disposal site also became choked with this type of material, evidencing longshore transport. In some cases, accretion occurred along the lower end of the seaward flank of the disposal bar, possibly as a result of slope adjustment and onshore sediment transport.

Final surveys showed accretion at the base of the foreshore, complete filling of the surf zone trough, a platform or new trough at the initial surf zone bar position, disappearance of the surf zone bar, and generally a more seaward surf zone boundary. Profiles adjacent to the disposal area showed slight accretion seaward of the surf zone. The predominant transport direction of disposal sediment was shoreward into the surf zone (in the direction of the coarsest native sand) and then in the direction of the longshore current.

During storms, the disposal bar served as a storm bar with major transport occurring in a shore-parallel direction along the bar axis. The increased width of the platform-disposal bar complex may provide additional benefits by increasing the amount of wave energy dissipation in the surf zone and hence, lessening erosion of the beach.

PREFACE

This report provides coastal engineers an evaluation of a beach nourishment concept which utilizes wave transport to move sand onto a beach from a shallow-water dump site. Knowledge of sand movement patterns, as well as properties of the physical setting, is critical for evaluating the validity of the concept and for providing planning criteria for disposal operations based upon the concept. This field experiment is the first of a series of continuing experiments to determine the effects of disposal at various water depths. The work was carried out under the coastal construction research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. Robert K. Schwartz and Frank R. Musialowski, formerly with CERC, now with the Department of Geology, Allegheny College, Meadville, Pennsylvania, and the U.S. Geological Survey, National Center, Reston, Virginia, respectively, under the general supervision of Dr. C.H. Everts, Chief, Engineering Geology Branch, Engineering Development Division, CERC.

The authors acknowledge the Plant Branch of the Operations Division, Directorate of Civil Works, OCE, for their testing and planning support, and the U.S. Army Engineer District, Wilmington, who carried out all operations and provided assistance in the monitoring program. In particular, special thanks are extended to W. Murden, OCE, and W. Sanderson, Wilmington District, whose support and assistance were indispensable. CERC was responsible for planning and conducting the monitor study of the placed material. Military personnel and equipment support were supplied by Fort Belvoir, Virginia, and Fort Story, Virginia. Personnel from the U.S. Army 86th Diving Detachment, Fort Belvoir, were instrumental to the success of the field operation.

D. Howard of the Wilmington District provided field liaison. Dr. R. Hobson and D. Prins of CERC assisted in field data collection. Special thanks are due to M. O'Keefe (Washington State University), who aided in field data collection and the tedious job of data reduction; R.O. Bruno (CERC), who donated much time and expertise in the data processing phase of the study; and Drs. C. Everts, Engineering Geology Branch, and R.J. Hallermeier, Coastal Processes and Structures Branch, who reviewed the manuscript.

Comments on this publication are invited.

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Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: C = (5/9) (F -32).

To obtain Kelvin (K) readings, use formula: K = (5/9) (F -32) + 273.15.

TRANSPORT OF DREDGED SEDIMENT PLACED IN THE NEARSHORE ZONE - *CURRITUCK* SAND-BYPASS STUDY (PHASE I)

by

Robert K. Schwartz and Frank R. Musialowski

I. INTRODUCTION

1. Purpose.

The Corps of Engineers is responsible for the dredging maintenance of navigation channels through small, shallow coastal inlets. Environmental and economic factors usually place prohibitive constraints on inland placement of dredged material. Moreover, both inland and deepwater placement of dredged sediment results in a permanent loss of sand to the overall littoral system. Although side-cast dredging has sometimes been fairly effective, the side-casted sand placed adjacent to a dredging site has a relatively high potential for reentering the entrance channel.

In 1975, the U.S. Army Engineer District, Wilmington, placed a split-hull barge, the *Currituck*, in service. The *Currituck* can transfer sediment excavated from coastal inlet entrance channels to a shallow nearshore zone downdrift of a dredged inlet (Fig. 1). When fully loaded, the *Currituck* can release its load (usually between 190 and 230 cubic meters) at a 2-meter-minimum water depth. For beach nourishment purposes, this sediment transfer operation is conducted with the view that the placed or dumped materials will be transported by wave-induced currents to the beach and surf zones, thus aiding natural sand bypassing around the inlet and nourishing shores adjacent to the inlet complex.

The offshore placement of dredged inlet sediment as an approach to beach nourishment is an attractive concept for several reasons. The split-hull barge-type of disposal operation is time-efficient and generally less expensive than alternate means of disposal. The system eliminates the need for double handling or for land-based equipment necessary to place sand on the beach. In addition, sand from the maintained part of the inlet is of excellent quality for beach nourishment due to its source relationship to the littoral zone and due to high-energy winnowing (sorting) conditions in the inlet itself. Moreover, recent studies indicate that the dredging (sediment-handling) process further improves the textural characteristics of the native sand, making it even more suitable for beach fill (Hobson, 1977a, 1977b). Finally, the size characteristics of inlet sand improve the chances of selective shoreward transport from the offshore zone. This final aspect is discussed further in the following sections.

The success of the offshore disposal operations is dependent upon sand placed seaward of the surf zone moving shoreward into that zone as a result of wave transport. An experiment was conducted during the summer of 1976 to test that concept, using the *Currituck* sand transfer system, and to examine the modification and net displacement of sediment placed in shallow water seaward of the surf zone along an open coast. This report discusses the placement, modification, and net transport of the sediment. A summary report on the initial findings was previously published (Schwartz and Musialowski, 1977).

Figure 1. The split-hull barge *Currituck* placing dredged sediment in shallow water just seaward of the surf zone.

2. Terminology.

The *offshore zone* is defined as that region of variable width extending from the breaker zone to the seaward edge of the Continental Shelf (American Geological Institute, 1972; U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) (Fig. 2). The *nearshore zone* is the indefinite zone extending from the low water shoreline well beyond the breaker zone, defining the area of nearshore currents, and including the inshore zone and part of the offshore zone (American Geological Institute, 1972; U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). The *inshore zone* is the zone of variable width extending from the low water shoreline through the breaker zone (American Geological Institute, 1972; U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). The principal dynamic zones comprising the nearshore include the swash zone, the surf zone, and the region seaward of the surf zone characterized by shoaling waves (Fig. 2).

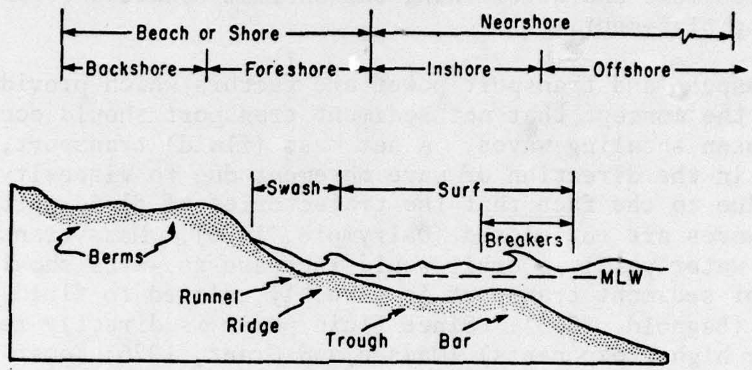

Figure 2. Coastal zone terminology and principal dynamic zones.

Overlap, thus, exists in the areas referred to by the terms nearshore and offshore. The selection of a distinct boundary for these areas is not easy, or perhaps even possible, due to the transitional nature of the zones, a lack of distinct physical criteria, and temporal-spatial variations in the properties of the zones (e.g., varying extent of the nearshore currents).

The seaward limit to this study lies within the innermost part of the offshore zone. Because the nearshore zone encompasses this part of the offshore zone, the term nearshore zone is used to refer to the overall subaqueous coastal setting of this study. The term offshore zone is used to refer to any point seaward of the surf zone. For purposes of data analysis and discussion in this study, the beach and nearshore is subdivided into beach, inshore, and offshore subzones.

The terms offshore and nearshore are commonly used in coastal studies. Researchers studying the subaerial beach, or both the combined beach and nearshore zones, sometimes refer to seaward losses of sand from the beach into the adjacent subaqueous zone as losses to the offshore zone (Watts, 1958; Caldwell, 1966, Gorsline, 1966; Everts, DeWall, and Czerniak, 1974; Nordstrom and Inman, 1975; Komar, 1976, pp. 291-294). Many laboratory and field studies involving sediment texture, currents, and sand transport in the same shallow region immediately seaward of the breakpoint, commonly refer to this zone as the nearshore zone (Cook and Gorsline, 1972; Davis and Ethington, 1976; Schwartz, in preparation, 1980). Alternatively, nourishment projects in which sediment is placed in the

same shallow zone are referred to as offshore nourishment projects. The anticipated benefits and most of the subsequent profile monitoring for those projects involve the beach and inner nearshore zone. In this study, as a consequence of shallow-water placement during high tide and seaward migration of the low tide breakpoint, some material was actually located in the surf zone, or, in the unequivocal nearshore zone.

3. Background on Sediment Movement.

The concept of offshore placement of dredged sediment as a means of beach nourishment is based on the likelihood of net shoreward transport of the placed sand. This section provides the rationale upon which the concept for shallow-water placement is based. Knowledge of how wave and wind conditions affect transport direction and rate is not only important to establishing the general concept, but also important for determining some criteria for the placement (time and location) of sediment and determining the optimum conditions for onshore transport following placement.

Wave mass transport and transport power are factors which provide a theoretical basis for the concept that net sediment transport should occur in the direction of unbroken shoaling waves. A net mass (fluid) transport, although small, is induced in the direction of wave movement due to viscosity (Sleath, 1974) as well as due to the fact that the trajectories of fluid particles under finite-amplitude waves are not closed (Dalrymple, 1976). Mass transport due to nonclosure of the water particle orbit would increase as waves shoal. In addition, the amount of sediment transport is directly related to fluid power expended on the bed (Bagnold, 1963). Since fluid power is directly related to velocity cubed (or higher exponents) (Madsen and Grant, 1976; Komar 1976b, p. 113) sand transport should be greater during the higher velocity landward flow associated with passage of the wave crest than the lower velocity seaward flow associated with the wave trough.

Although evidence supports sediment transport in the direction of wave advance, it is generally accepted that the added presence of an unidirectional current (e.g., wind-driven current or tidal current) can alter the direction of net transport, or produce a net transport where wave transport is oscillatory (Bagnold, 1963; Komar, 1976a, p. 299). Cook and Gorsline (1972) reported that in southern California bottom-drift direction was associated with wind-shear effects as well as swell characteristics. They suggested that onshore breezes caused compensatory offshore flow at depth and that offshore breezes aided shoreward bottom flow. Seaward bottom drift was associated with onshore winds and short-period waves; long-period swells were associated with shoreward drift. Cook and Gorsline concluded that the conventional concept of wave drift was inadequate in that net offshore water transport was frequent. King and Williams (1949) conducted wave tank experiments superimposing onshore winds of 13 centimeters per second. They found that the landward movement due to wave action alone was converted to a slight seaward transport.

In spite of evidence of reversals of bottom-drift direction with certain wind and wave conditions, or depending upon the superposition of unidirectional currents, field studies utilizing sand tracers placed outside the breaker zone show a predominance of onshore transport. Vernon (1965) showed that tracer grains dispersed landward and more rapidly at shallower depths than in deeper water, and that fine sand underwent greater movement than coarse sand. Similar findings

resulted from radioactive sand-tracer studies conducted by the Coastal Engineering Research Center (CERC) (Duane, 1976; Schwartz, in preparation, 1980). The CERC results were that the fine-grained sand tracer (which matched the offshore bed size) and the coarser tracer moved landward, and the very fine-grained tracer moved alongshore and slightly offshore. Vernon (1965) showed that very fine-grained sand moved shoreward but in a very diffuse pattern.

In shallow water, but outside the breaker zone, waves alone probably cause selective sorting. The result is a shoreward transport of coarser sediment due to the asymmetry of orbital flow (Cornish, 1898; May, 1973; see discussion of null-point concept by Komar, 1976a). Many laboratory and field studies indicate that in the nearshore zone, transport of relatively coarse sand is commonly landward. Some wave tank experiments show that beach accretion and nearshore erosion are generally associated with low waves, long wave periods, and coarser sand sizes (King and Williams, 1949; Rector, 1954; Scott; 1954, Sunamura and Horikawa, 1974). Alternatively, beach erosion and nearshore accretion are associated with high waves, short wave periods, and finer sand sizes. This is in accordance with field observations indicating that beach profiles generally accrete during fair-weather periods (swell conditions) and erode during storm periods (Shepard and LaFond, 1940; Shepard, 1950; Bascom, 1951; Inman and Rusnak, 1956; Gorsline, 1966; Nordstrom and Inman, 1975). As an example, in southern California sand transported offshore during the winter seasonal change was deposited as a sheet between 3- to 9-meter water depths (Nordstrom and Inman, 1975). In response to following summer swell conditions, beach accretion resulted from a progressive onshore migration of sand from water depths of less than 10 meters.

One aspect of storm transport pertinent to sediment placement is that with storm waves the sand within the surf zone is transported seaward toward the breaker zone, whereas sand seaward of the breaker zone continues to move shoreward (King and Williams, 1949; King, 1972). Some workers contend that this convergence of transport may result in the formation of a storm bar (King and Williams, 1949; Komar, 1976a). This is pertinent to sediment placement; if the sand is moved seaward during mild storms to form a storm bar, water depths for the storm bar should be relatively shallow and therefore allow for onshore movement of material during ensuing swell conditions. Also, if placement is in relatively shallow water but seaward of storm breakpoint position, disposal sediment may move onshore, as desired, even during storm conditions.

In view of theoretical, laboratory, and field data, it is likely that sand placed in relatively shallow water outside the surf zone could undergo landward transport into the surf zone. The probability of shoreward transport would be maximized by placing material as shallow as possible to take advantage of mass transport effects, by placing material during the onset of fair-weather conditions (i.e., long wave period, low wave height, and usually offshore winds), and by placing sand-sized material that is coarser than the native material at the disposal site.

4. Other Offshore Nourishment Experiments.

Laboratory and field experiments in placing sand seaward of the breaker zone have been conducted to examine the concept of offshore nourishment. Particularly successful was a two-dimensional laboratory study which simulated small and large storm conditions of the Great Lakes wave climate (Kamphuis and Bridgeman, 1975). Relatively coarse sand (median size = 0.6 millimeter), which was placed

immediately seaward of the offshore bar (surf zone bar), moved shoreward and accreted to the beach, as long as placement was in the simulated early summer wave cycle (small storm wave conditions) and was as high on the profile as possible within the reach of summer waves. The material placed below the critical depth for entrainment was moved seaward by large storm waves (winter conditions) and did not return shoreward in response to ensuing small storm waves. Similarly, seaward "trapping" resulted from sediment placement on the seaward adjusted winter storm profile when followed by summer (small storm) waves. Presumably, the seaward displaced sand was below a critical depth for entrainment by the small-scale waves. The study demonstrates that, at least in the laboratory, onshore transport and accretion of placed sand should occur as a result of certain placement conditions, i.e., the location on the profile and the season. It is questionable though that such loss would be permanent in the field where a wider and more continuous spectrum of wave conditions occurs. Although not a beach or offshore nourishment experiment, Nordstrom and Inman's (1975) study provides support that such a loss may not be permanent in the field. After examining seasonal variation in profiles, they concluded that sand was transported offshore from the beach face during the winter seasonal change and deposited in depths of -3 to -9 meters. This change occurred abruptly with the coincidence of high waves and tides. They further concluded that summer beach accretion resulted from a progressive onshore migration of sand from water depths of less than 10 meters. A net offshore loss was *not* apparent.

Field experiments involving offshore placement have only been partially successful. Experiments in which the disposed material showed neither systematic movement nor any evidence of benefit to the beach were conducted at Long Branch, New Jersey (Hall and Herron, 1950; Harris, 1954) Atlantic City, New Jersey (Hall and Watts, 1957), and Santa Barbara, California (Wiegel, 1964). Approximately 460,000 cubic meters of sand was placed 800 meters offshore from the Long Branch beach in 10- to 12-meter water depths. The average grain size of the placed sand was 0.34 millimeter, the offshore sand 0.32 millimeter, and the beach sand 0.66 millimeter. It was concluded that most of the time, wave action was not sufficient to move sand at that depth, and when sand did move, it did so "haphazardly." At Santa Barbara, approximately 153,000 cubic meters of sand was dredged from the harbor and placed in 6.7 meters of water 300 meters from shore. The placed sediment formed a mound about 670 meters long and 1.5 meters high. Surveys conducted 9 years later showed essentially no change in the mound, indicating no significant transport had occurred. Although sand was placed in shallower water for the Atlantic City experiment (water depth = 4.5 to 6.1 meters), there was insufficient information to evaluate the apparent failure of onshore nourishment. Harris (1954) concluded that for sand to move shoreward and benefit the beach, placement should be in depths less than 6 meters.

Offshore nourishment projects at Copacabana Beach, Brazil (Vera Cruz, 1972) and the Limfjord Barriers, Denmark (Mikkelsen, 1977) were highly successful. Similar aspects for both of these projects are: (a) The placed sand was similar in size (or slightly coarser) than the native beach sand, (b) placement was in depths between the -4- and -6-meter contour, and (c) placement was generally between shore-normal structures. The Copacabana Beach is crescentic in form and bordered at each end by a natural promontory. Disposal for the Limfjord Barrier project was between and slightly seaward of two groins. In both cases, direct onshore accretion of the beach resulted. At Limfjord, the disposed sand formed a bar which moved continually toward the beach, and, approximately 1 year following disposal, the profile became a seaward adjusted form without any bar.

Mikkelsen (1977) suggested that three conditions may have contributed to the Limfjord profile development: (a) The borrow sand was coarser than the native sand; (b) the groins acted as impermeable barriers and cut off longshore drift away from the site; and (c) a higher-than-normal frequency of offshore winds may have occurred, thus aiding onshore bedload wave transport.

II. FIELD PROCEDURE AND DATA ANALYSIS

1. Geographic Setting.

The entrance channel to New River Inlet, located approximately 60 kilometers northeast of Wilmington, North Carolina, was the dredging site for this study (Figs. 3 and 4). The disposal site was located 2 kilometers southwest of the inlet along West Onslow Beach. The beach throughout this vicinity is approximately 60 meters wide and backed by a vegetated foredune. The study site is located at the northeastern part of a barrier island, which is only slightly developed with a scattering of private dwellings in the vegetated barrier flat landward of the foredune. The beach is used solely for recreational purposes. A fishing pier, located 3.5 kilometers southeast from the inlet, is the only structure present along this section of coastline.

2. Disposal Procedure.

During the period, 19 July to 13 August 1976 (26 days), 26,750 cubic meters of sand was dredged from New River Inlet (Figs. 2 and 3), transported to the disposal site by the *Currituck*, and placed along a 210-meter coastal reach within the study area. Although the *Currituck* has a minimum water depth capability of about 2 meters, a tidal range of about 1 meter and varying swell conditions resulted in the actual disposal area extending from the 1.8- to 4.0-meter depth contour mean low water (MLW). A 30-meter-wide shore-normal zone, in which no sediment was to be placed, flanked both sides of the disposal reach. Some sediment, though, was inadvertently placed within the southwest flank, between ranges -9+00 and -10+00, beyond the designed disposal limit. Monitoring of the study area began a week before disposal and extended through and subsequent to the disposal period until 19 October 1976, 71 days following the final disposal date (Figs. 5 and 6).

3. Survey Data.

A 270- by 300-meter area spanning the beach and nearshore zone was selected for measuring combined beach and nearshore profiles. The shore-normal dimension (300 meters) extended from the base of the foredune ($\sim$ +3 meters MLW) seaward 240 to 270 meters beyond MLW to an approximate water depth of -4.5 meters MLW.

Profiles extending across the beach and nearshore zone were measured at 30-meter intervals. The beach of each profile was measured using standard rod and tape surveying techniques. A stadia board attached to a towed, bottom-riding sea sled was used to obtain bathymetric data seaward of the beach (Musialowski, Schwartz, and Teleki, 1977). The sled was towed seaward from the beach along a survey range line by an amphibious vehicle (LARC-V) and detached at an offshore point. Position and elevation data were recorded as the sled was pulled landward by a shore-based winch. In several cases, the sled moved slightly off line which led to outer profile variability in the true position and shape of profile

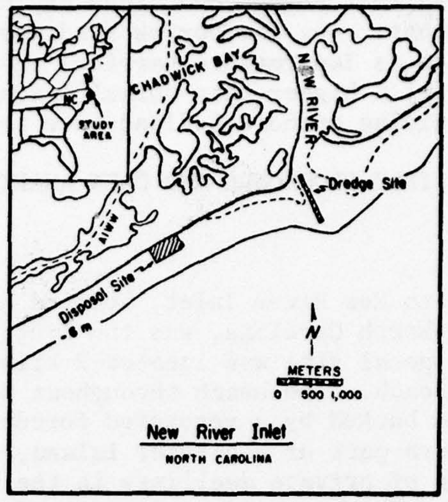

Figure 3. Location map of study area near New River Inlet, North Carolina.

Figure 4. Aerial view of New River Inlet and the study area. Dredged sediment was placed between the two innermost dye sources. The dye pattern shows a wind-driven current moving toward the northeast.

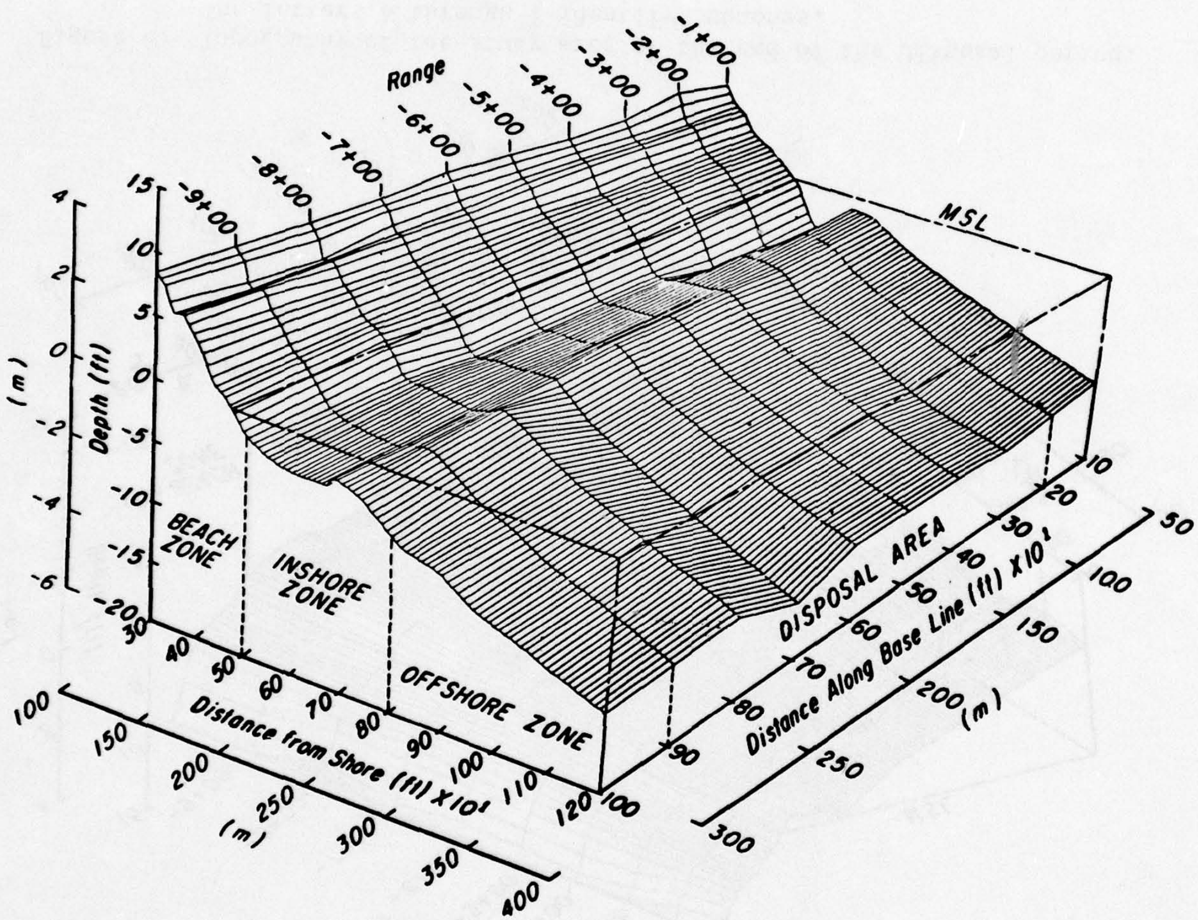

Figure 5. Topography of the study area before disposal.

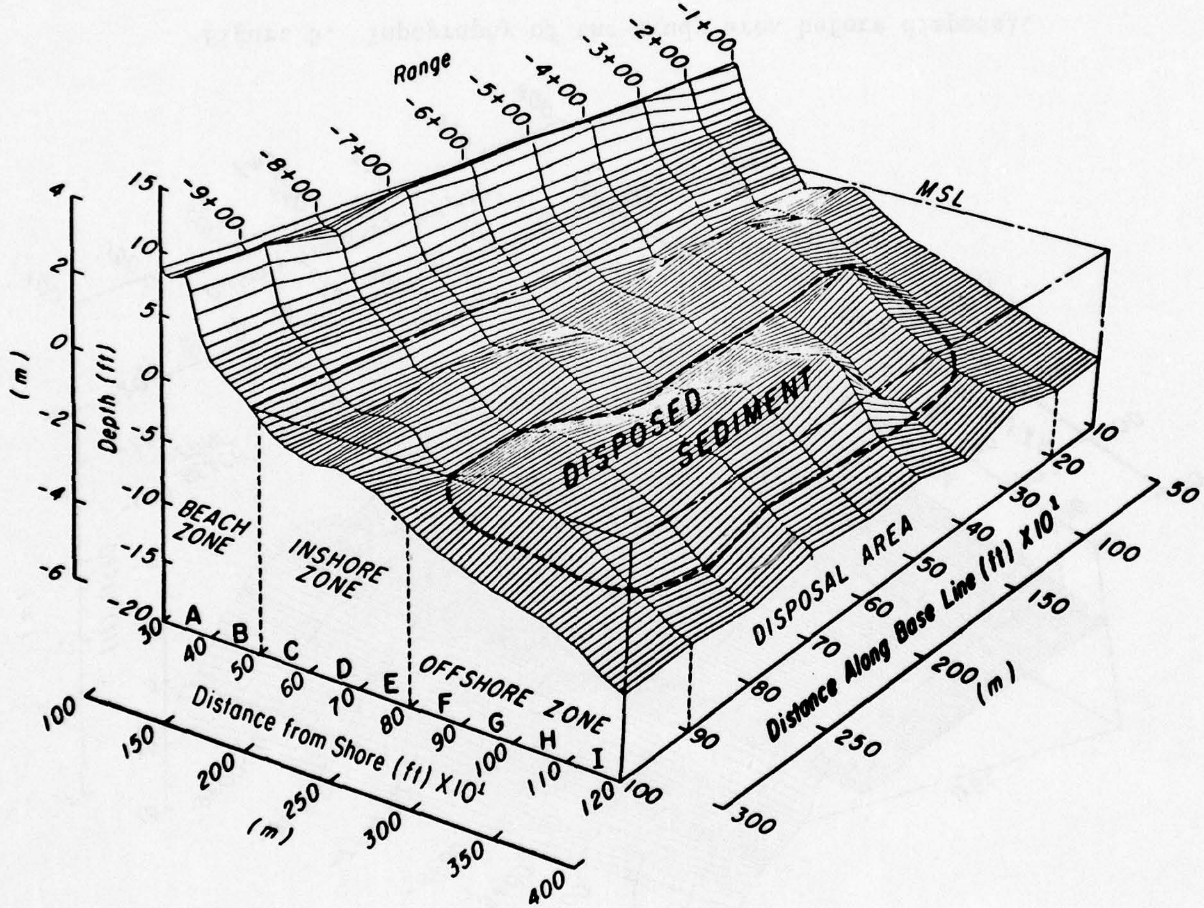

Figure 6. Topography of the study area at the end of the disposal period. The letters A through I identify subzones.

features. For this reason, data interpretation is based primarily on shape and volume trends, not individual data points.

Profile data were edited for survey error and digitized. Volumes were calculated for 9.3-square meter areas between adjacent profiles, using an elevation base of -6 meters MLW and the seabed elevation at each corner of the area.

Shore-parallel zones within the study area are defined to examine changes in profile shape and volume. The area is divided into the beach, the inshore, and the offshore zones (Fig. 5). The beach zone, which contains the entire backshore and foreshore, extends seaward to about -1 meter MLW. The inshore zone spans the surf zone and consists of a trough, bar, and seaward bar flank. The inshore-offshore zone boundary is positioned on the seaward flank of the surf zone bar between -1.5 and -1.8 meters MLW. The offshore zone extends seaward to about 240 meters beyond MLW (365 meters from base line) to maximum water depths of -4.5 meters MLW. Although individual profiles were measured to more seaward distances, the 365-meter base-line distance was common to all profiles and thus used as a seaward study limit for digitizing the profile data.

4. Sediment Samples.

Sediment samples were collected from the upper 2 centimeters of the bed at a 7.6-meter interval along a single profile line (-5+00) near the middle of the study area. The close sample spacing allowed textural representation of all dynamic zones and profile features. The sediment was sieved at a 0.25-phi interval using U.S. Standard sieves and statistics were calculated using the equations of Inman (1952).

5. Wave and Current Data.

Longshore current velocity and direction, breaker height and period, angle of wave approach, and wind velocity and direction were collected from 14 July to 16 September, using Littoral Environment Observation (LEO) techniques (Bruno and Hiipakka, 1973). Aerial photography was used to document beach and disposal pile configuration and to examine nearshore circulation in the disposal area. Several short-term ($\sim$ 2 hours) current-meter experiments using the sea sled system (Musialowski, Schwartz, and Teleki, 1977) were conducted to document current distribution along the nearshore profile.

III. PHYSICAL CONDITIONS AT STUDY AREA

1. General.

Before disposal, the beach and nearshore zone contained a single bar which was shore-parallel, semicontinuous, and located in the outermost part of the surf zone. In general, the beach and nearshore zone consisted of fine-grained (Mn $\simeq$ 2.8 phi, 0.14 millimeter), well-sorted ($S\phi \simeq 0.40$) sand.

The predicted tidal range during the study period was mean = 1.0 meter and spring = 1.1 meters. The average (mean) breaker height ($\bar{H}_b$) was 0.55 meter and average (mean) period of breaking waves ($\bar{T}_b$) was 7.3 seconds. Standard deviation for the breaker height was 0.26 meter and 1.8 seconds for the breaker period.

The distribution of observed breaker heights and wave periods is shown in Figures 7 and 8. Winds were predominantly from the south, southwest, and west

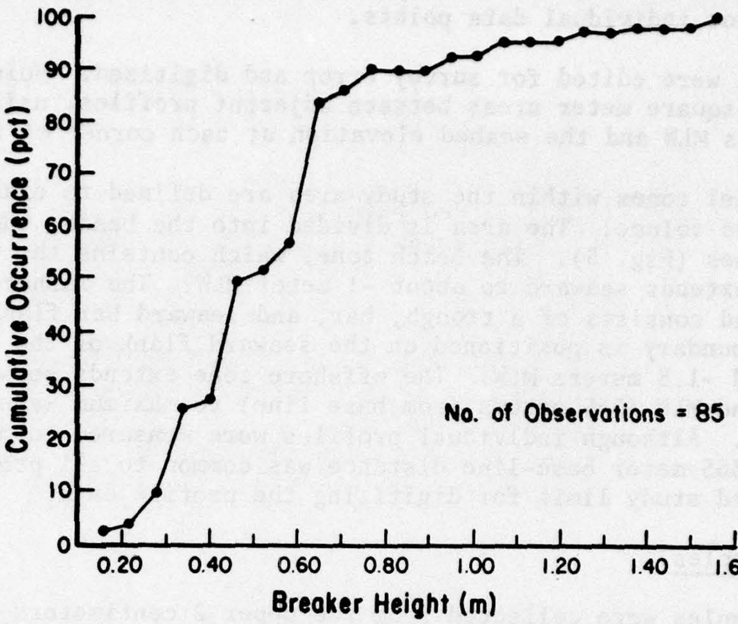

Figure 7. Cumulative distribution of breaker height, H_b, observed at the study site.

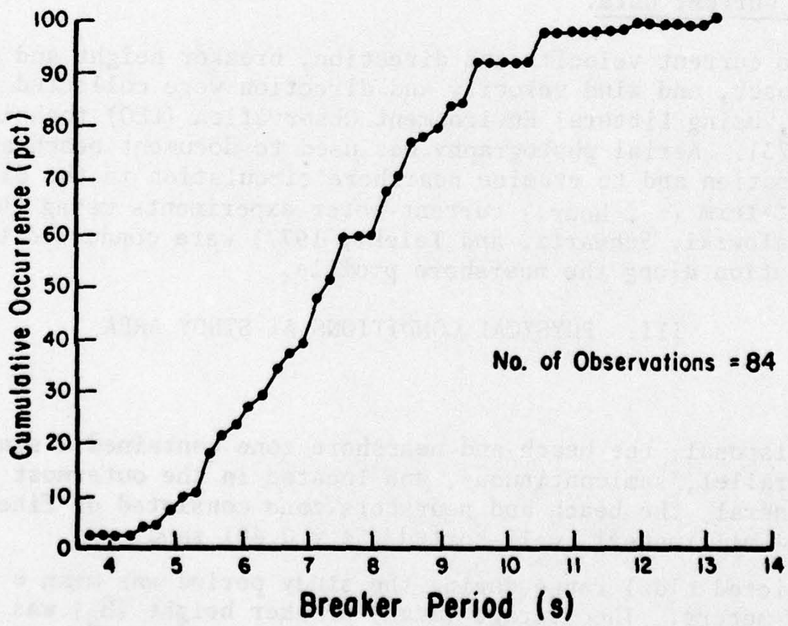

Figure 8. Cumulative distribution of breaker period, T_b, observed at the study site.

during the disposal period (Fig. 9). During the postdisposal period, northerly winds increased in frequency and speed.

The experiment extended from a period of "summer oceanographic conditions" into a period of oceanographic conditions more typical of the fall, winter, and spring seasons (Fig. 10). The summer condition was characterized by southerly to southwesterly winds and a southerly swell direction. Winds during July were commonly diurnal with a low-velocity breeze from the land in the morning and a higher velocity, land-directed breeze in the afternoon. Breaker period was typically less than 6 to 7 seconds and breaker heights usually less than 0.6 meter. The longshore current was northeast, toward the inlet, with an average measured speed of 18 meters per minute.

The "winter oceanographic condition" was characterized by northerly to easterly winds and a wave swell from the east. Breaker period was typically greater than 6 to 7 seconds and breaker heights commonly ≥ 0.6 meter. Longshore currents were typically southwest at an average measured speed of 23 meters per minute. A number of northeasterly storms occurred during September and October. Wave data from Atlantic Beach, North Carolina (∿ 58 kilometers northeast of New River Inlet) show an increased occurrence of storm wave conditions during the latter part of the study period (Fig. 11).

Dye studies indicated that the juncture between wave-induced currents and strong tidal inlet currents was located near the outer margin of the ebb tidal delta. The disposal area, 2 kilometers downcoast from New River Inlet, was judged to be beyond any direct influence of inlet-associated tidal currents.

2. <u>Storms</u>.

The criterion for a storm wave condition is arbitrarily chosen to be the occurrence of breaker heights in excess of 0.6 meter. More than 70 percent of the measured breaker heights were less than 0.6 meter (Fig. 7). The time-sequence LEO plot for the study area shows well-defined periods of relatively high breakers (> 0.6 meter). These storm periods represent swell and local sea conditions--the local sea usually being a response to extratropical storms or more extreme summer (southerly) winds.

Local seas of the summer diurnal wind period produced maximum average breaker heights between 0.6 and 0.8 meter. These waves approached generally from the south. Waves from the northeast, e.g., those associated with northeasters, produced maximum average breaker heights between 0.9 and 1.5 meters. Wave gages located approximately 58 kilometers north (Atlantic Beach) and approximately 54 kilometers south (Wrightsville Beach) of New River Inlet showed that for a 4-year period, maximum significant wave heights (recorded at water depth ∿ 5.2 meters) usually range from 0.9 to 1.8 meters in the summer and from 0.9 to 2.7 meters in the winter. These wave heights represent the range in storm wave height in the vicinity of the study area. Observed breaker periods for storm waves at the study site ranged between 4 and 12 seconds depending upon whether local sea or swell conditions existed.

3. <u>Wind-Driven Currents</u>.

Wind-driven currents occurred periodically and were effective throughout the nearshore zone. For example, on 21 July during the summer diurnal wind period,

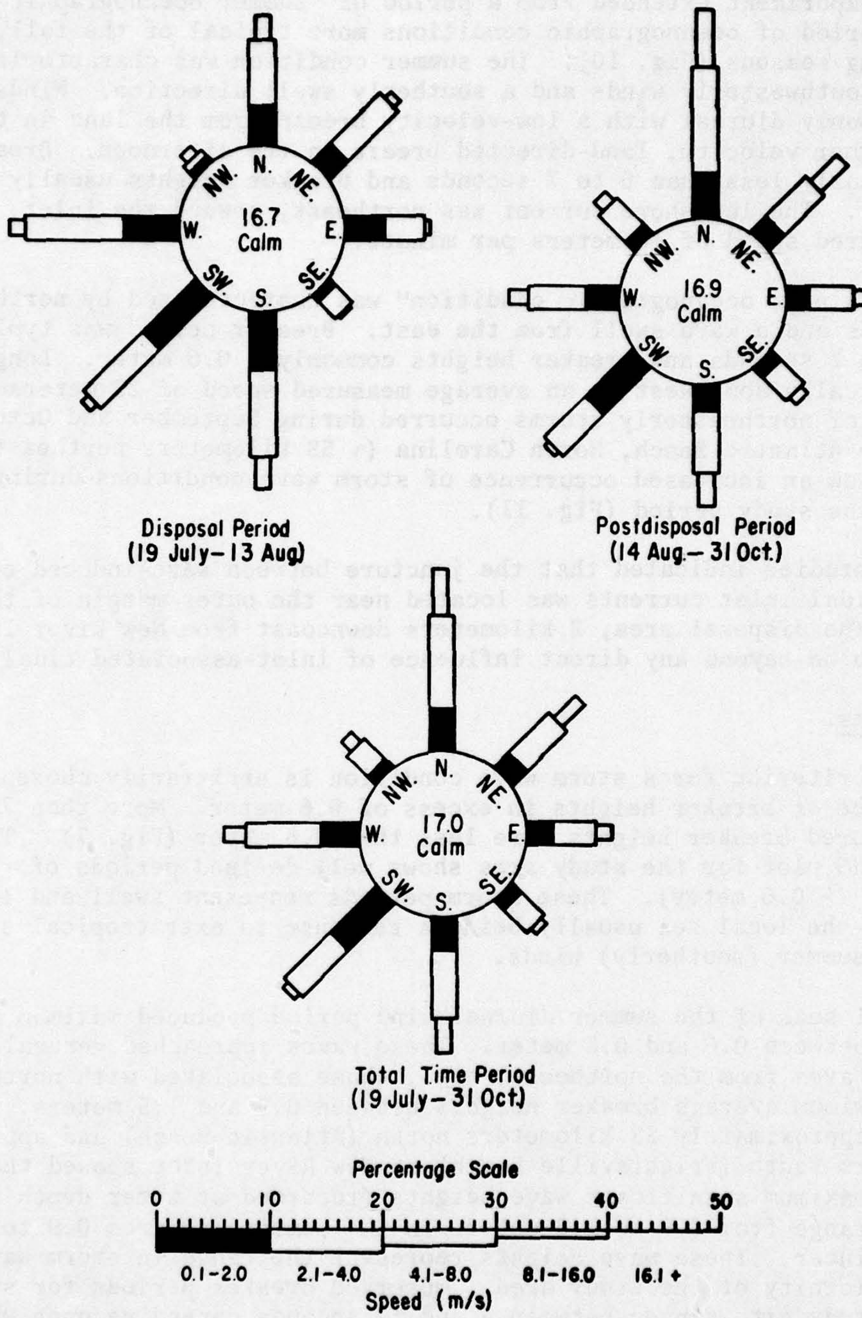

Figure 9. Wind rose diagrams for the New River Inlet area.

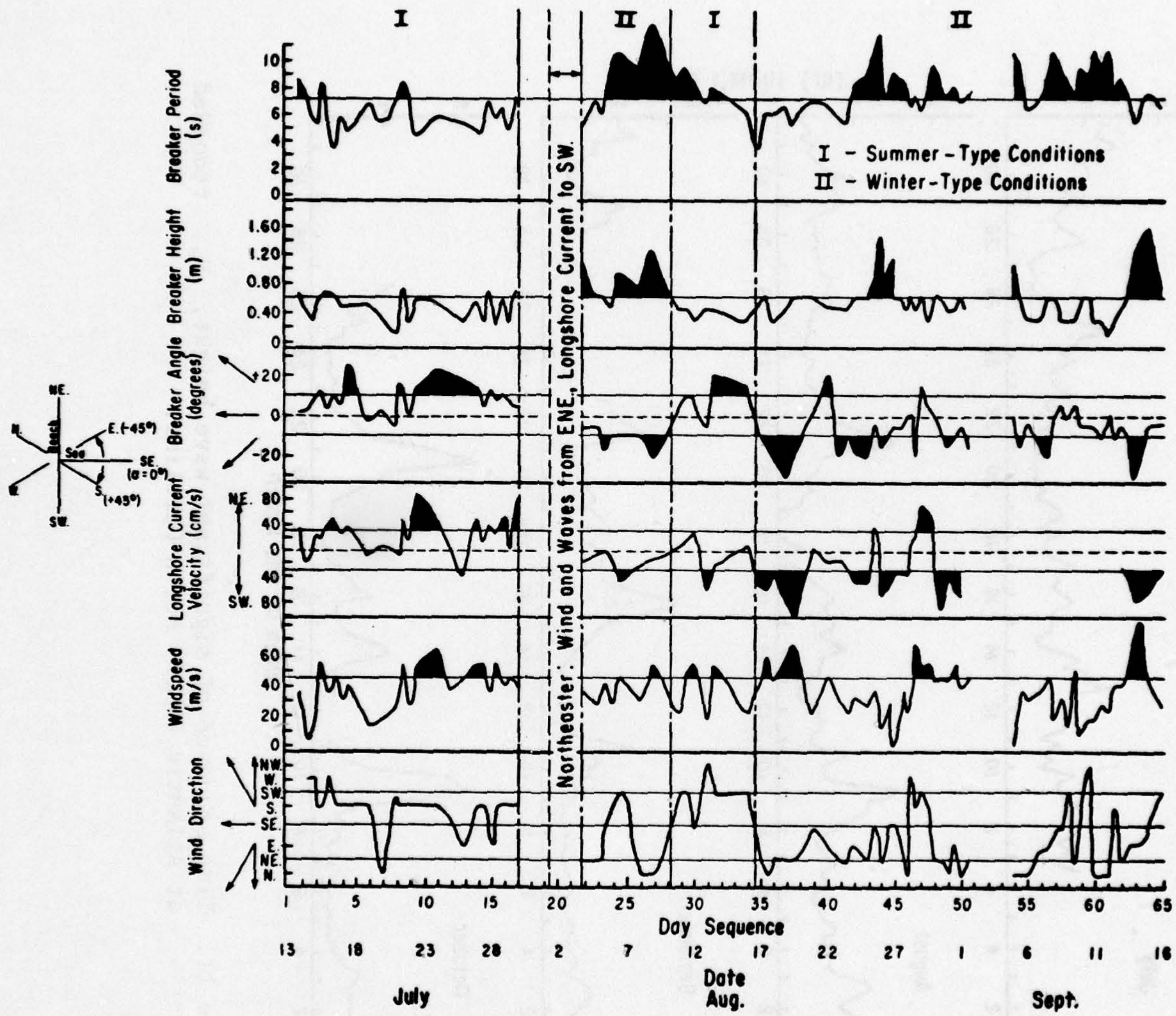

Figure 10. Time sequence of environmental properties (LEO) observed at the study site (I indicates summer-type conditions, II winter-type conditions). Major peaks for some of the data sets are stipled to aid in visual correlation between the sets.

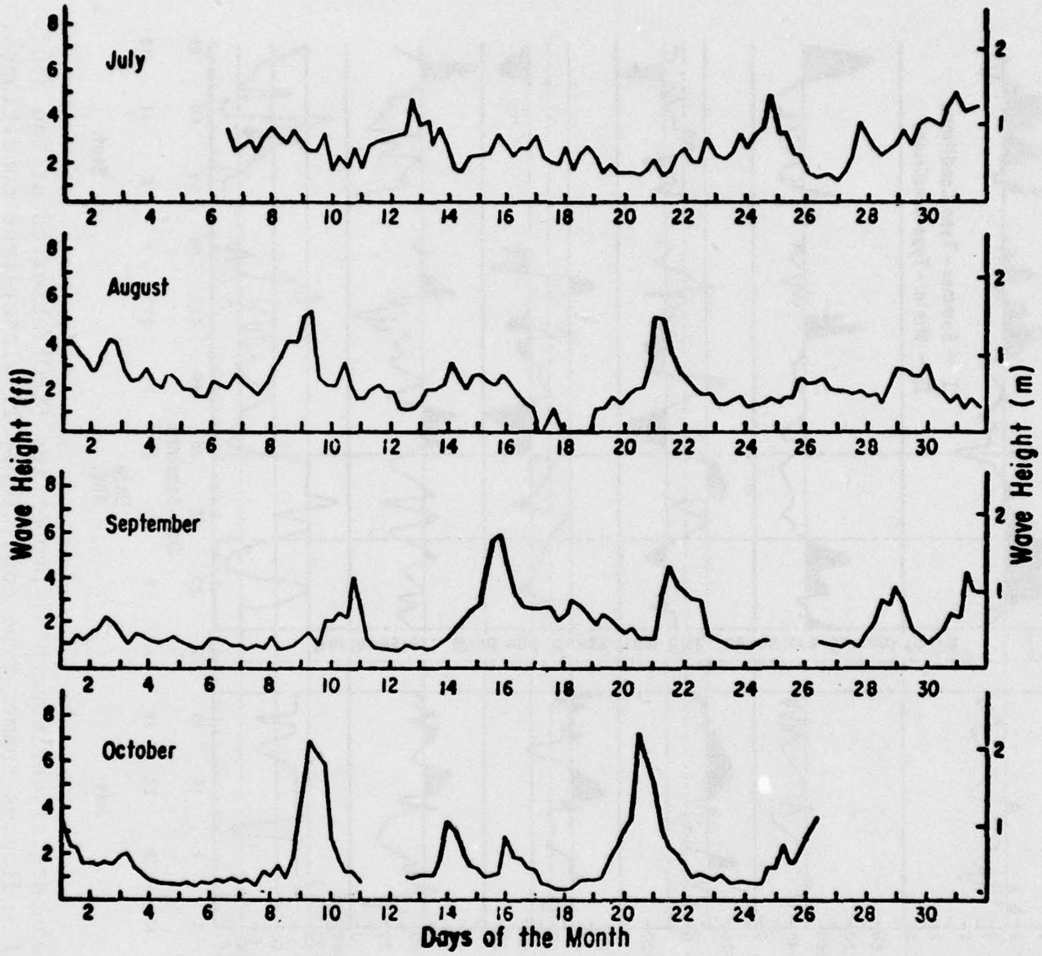

Figure 11. Time sequence of significant wave height, H_s, recorded at Atlantic Beach, North Carolina.

a combined swell and local sea condition existed. Associated with the local sea was the occurrence of an essentially shore-parallel wind-driven current. The wind-driven current (average surface velocity = 18 centimeters per second), which was documented with dyes, existed from the offshore at least up to the edge of the surf zone (Fig. 4). Inside the surf zone, the longshore current velocity, also measured by dyes, was 40 centimeters per second and in the same direction as the wind-driven current.

A current meter study was conducted on 24 July under conditions very similar to those on 21 July. General oceanographic conditions during the test were average breaker height = 0.55 meter, breaker period = 5.7 seconds, breaker (orthogonal) angle = 13° (south of normal), and longshore current speed = 41 centimeters per second from the southwest. Both a swell and a local sea existed. Wind velocity was ≈ 23 kilometers per hour and essentially shore parallel at the time of the experiment. Current meter measurements (1 meter above the bed) showed average shore-parallel speeds of 40 to 50 centimeters per second in the surf zone and average wind-driven current speeds generally exceeding 15 centimeters per second in the adjacent offshore zone (Fig. 12).

Wind and wave conditions similar to those associated with the measured wind-driven currents were observed to occur somewhat frequently during the study period.

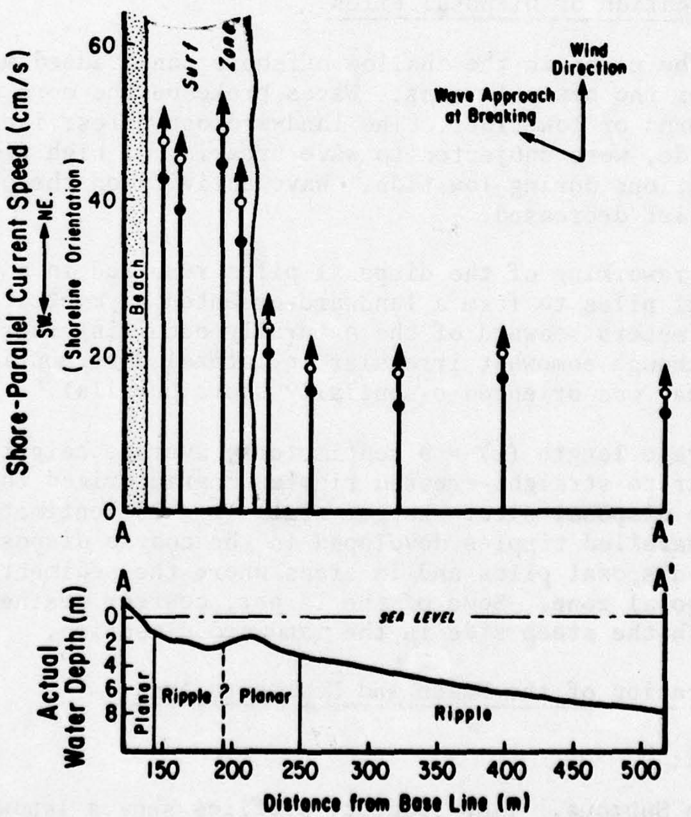

Figure 12. Shore-parallel current speeds measured across the nearshore zone on 24 July 1960. The data points on each vector represent percentile levels of the current speed distribution. The lower diagram shows the profile shape and the general bed-form type across section A-A.

IV. RESULTS

1. Disposed Sediment.

The *Currituck* released sediment at an actual water depth of about 2 meters, under calm or minor swell conditions. Depending upon tide level, i.e., migration of the 2-meter depth contour, and wave conditions, sediment was placed in a more landward or seaward position. Most of the disposed sediment dropped, with negligible spreading, to the ocean bottom to form a pile with the long axis oriented in a shore-normal direction. A relatively small amount of fine-sized sediment moved in suspension away from the pile. Individual pile shapes were rectangular ($\sim$ 9 by 25 meters) with relief dimensions ranging up to 1.8 meters.

Immediately following disposal, high-angle slopes (20°) were characteristic of the pile sides. Piles were placed adjacent to and as close to each other as possible in the alongshore direction. A local shoal zone was created with minimum water depths of 0.6 meter (Fig. 6). The placed sand (composite mean = 0.49 millimeter) was coarser than the average size of native sand (mean $\simeq$ 0.14 millimeter) at the point of disposal in the offshore zone as well as coarser than the composite grain size of the entire profile (composite mean = 0.21 millimeter).

2. Short-Term Modification of Disposal Piles.

The presence of the piles in the shallow offshore zone caused waves to deform locally and break over the new pile tops. Waves broke on the more seaward-placed piles only during storms or low tides. The landwardmost piles, i.e., those placed during high tide, were subjected to wave breaking at high tide, and rigorous surf zone conditions during low tide. Wave activity on the piles decreased with time as pile relief decreased.

Wave and current reworking of the disposal piles resulted in a gradual coalescing of individual piles to form a landward-oriented asymmetrical disposal bar located 60 to 90 meters seaward of the naturally occurring surf zone bar (Figs. 5 and 6). Although somewhat irregular in lateral distribution and topography, the disposal bar was oriented essentially shore parallel.

Small-scale (average length ($\bar{L}$) $\simeq$ 9 centimeters, average height ($\bar{H}$) $\lessapprox$ 1 centimeter), irregular to straight-crested ripples characterized the indigenous fine-sized bed of the disposal site. Larger scale ($\bar{L}$ = 25 centimeters, $\bar{H}$ = 5 centimeters), shore-paralled ripples developed in the coarse disposal sediment near the base of the disposal piles and in areas where the sediment spread laterally in the disposal zone. Some of the larger, coarser grained ripples were asymmetrical with the steep side in the landward direction.

3. Long-Term Modification of the Beach and Nearshore Area.

a. Profile Shape.

(1) Offshore Subzone. Time-sequence profiles show a landward migration of the disposal bar (Fig. 13). During the initial part of the postdisposal period, the disposal bar was located farther offshore in slightly deeper water. The migration rate (lateral movement of the bar crest) was greatest, often between 2.5 and 4.5 meters per day, when the bar relief was relatively high. The rate of movement was sporadic, varying with the degree of wave activity. In

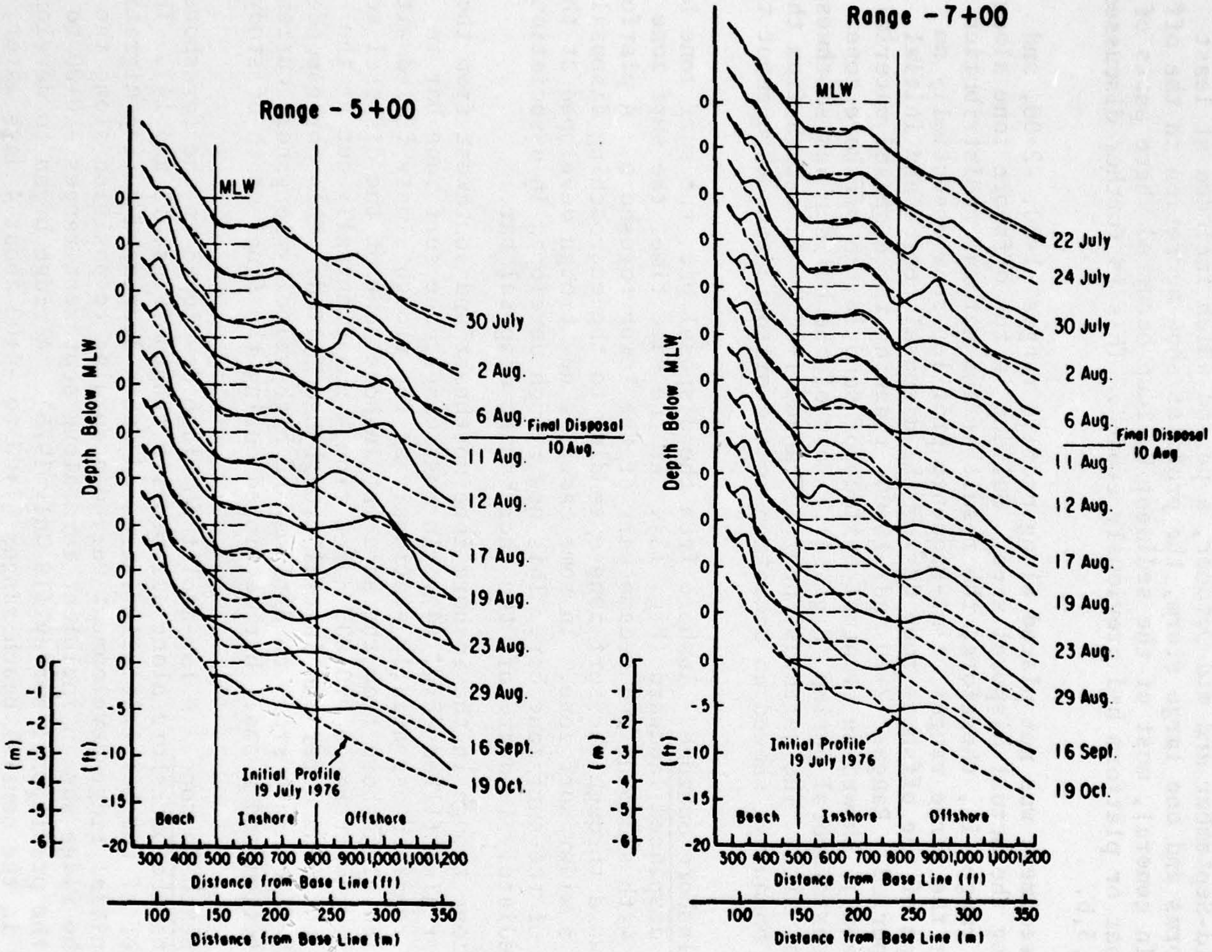

Figure 13. Time sequence of profile shape referenced to a predisposal survey (19 July 1976). Ranges -5+00 and -7+00 were located within the disposal area.

general, as the disposal bar approached the surf zone, the migration rate of the bar crest diminished, the disposal bar relief decreased, and the bar shape became less prominent. During the 9-week survey period following disposal, the disposal bar form never reached the initial position of the natural surf zone bar. Where the disposal bar became adjacent to the surf zone, the disposal bar form was either eliminated or became rounded and much reduced in relief.

Between mid-September and mid-October, a period which included at least five minor storms and one large storm, the profiles show accretion in the offshore zone. In general, most of the sediment buildup occurred where parts of the disposal bar or platform had previously eroded. This is further discussed in Section IV,3,b.

Disposal sediment was not placed along profile ranges -1+00, -2+00, and -10+00 flanking the actual disposal area. Buildup in the offshore zone along these profile ranges is, therefore, the result of the natural redistribution of sediment. For the three ranges, time-sequence profiles show essentially no change in shape of the offshore zone during the disposal period and initial postdisposal period. Ranges -2+00 and -10+00, flanking the disposed material ($\sim$ 15 meters away), showed an eventual buildup of sand in the offshore zone later in the postdisposal period (Fig. 14). Most of the buildup was southwest of the disposal site. The northeast profile range -1+00 ($\sim$ 45 meters from the disposal area boundary) showed no accretion in the offshore zone throughout the study period.

(2) Inshore Subzone. Inshore from the disposal bar, the surf zone bar eroded or was displaced landward (Fig. 13). At the same time, the surf zone trough filled with sediment and became part of the lower foreshore. A platform developed seaward through the surf zone extending to the encroaching disposal bar, creating a wider surf zone. In some cases, a new trough developed at the original site of the surf zone bar. This new trough developed in association with, and immediately landward of, the encroaching disposal bar.

The surf zone trough in the inshore zone northeast and southwest from the disposal sector also filled (Fig. 14). In most cases, the surf zone bar in these regions remained essentially stationary as the trough simply filled with sediment carried alongshore from the adjacent inshore zone of the disposal sector. At the southwest range -10+00, a new trough was eventually cut at the surf zone bar position after the initial trough had filled. This corresponded with a period of moderate storm conditions and high-velocity longshore currents. The trough refilled and a small bar developed during the final month of study.

(3) Beach Subzone. A low-amplitude ridge developed in the foreshore and migrated to the backshore along all profile ranges (Figs. 13 and 14). The size and relief of the bar initially increased, then decreased during migration. The time of initial ridge development varied according to position along the coastline. The ridge was in incipient form along southwest ranges -10+00 to -8+00 during the predisposal survey (19 July 1976). A ridge began to develop northeastward in the central beach ranges -7+00 to -4+00 about 4 days later, and to develop farther upcoast (ranges -3+00 to -1+00) 10 to 11 days later. The ridge persisted throughout the survey period (average of 55 days).

Overall change in the foreshore was less apparent. In general, slight scour occurred in the intertidal zone, and accretion, associated with filling of the landwardmost margin of the trough, occurred in the subtidal zone.

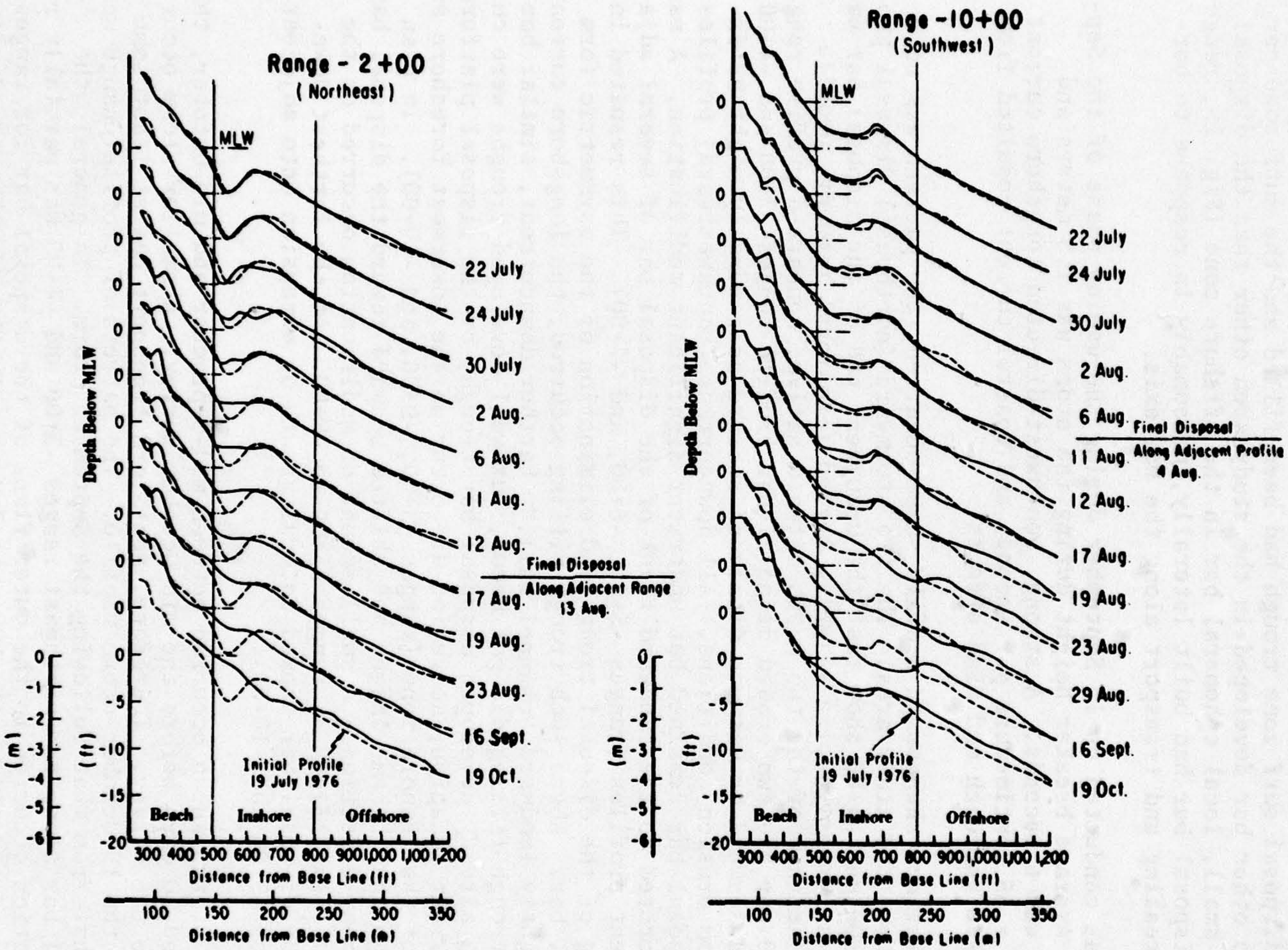

Figure 14. Time sequence of profile shape referenced to the predisposal survey (19 July 1976). Ranges -2+00 and -10+00 flank the disposal area.

b. <u>Storm Effect on Profile Shape</u>. Although a number of storm events occurred, the only significant profile change to be documented was that associated with a mid-September northeaster (14 to 16 September), the largest coastal storm that had occurred during the study up to that time. Before the mid-September storm, the predisposal surf zone trough had been filled and the surf zone bar eliminated. No other bar developed in the study area other than the disposal bar and a very small, local ephemeral bar in the offshore zone (Fig. 15, range -1+00). The disposal bar had built laterally, presumably in response to bar-induced wave breaking and transport along the bar axis.

A survey was conducted on 16 September during the waning phase of the September storm. Average breaker height during the storm was 1.5 meters and breaker period was 6 seconds. A strong, southwest-directed longshore current (average speed = 65 centimeters per second) and coastal current resulted from the easterly wave approach and wind effects.

Although distinct changes in profile shape occurred, the pattern was not uniform throughout the study area. The two stormward (northeast) disposal profile ranges -3+00 and -4+00 show that the upcurrent end of the disposal bar was eroded to form a nonbarred or a slightly barred (erosional remnant) profile (Fig. 15). In neither of the two northeastward native, nonbarred profile ranges -1+00 and -2+00 nor the two eroded disposal bar profile ranges -3+00 and -4+00, did a bar build seaward or was one displaced seaward as generally might be expected for storm erosion conditions. All downcurrent (southwestward) profiles showed the disposal bar remained but underwent significant modification. A mass of sediment accreted to the landward flank of the disposal bar of several adjacent, downcurrent profiles (ranges -5+00, -6+00, and -7+00). This resulted in partial filling of the disposal trough and elimination of the asymmetric form of the disposal bar. Where such trough filling occurred, the longshore current cut a new, slightly landward "channel wall." Farther downcurrent, similar bar accretion and trough filling did not occur, but well-developed troughs were cut deeper into the already developed disposal bar trough, or the disposal platform. In this downcurrent location, accretion did occur on the lowermost foreshore and landward side of the inshore zone (ranges -8+00, -9+00, and -10+00). In plan view, the trough thus became larger and shifted seaward toward the disposal bar in the downcurrent direction. A small amount of modification occurred on the disposal bar's seaward flank at ranges -5+00 to -8+00. At the farthest downcurrent end, the disposal bar showed lateral growth or extension onto adjacent profiles (ranges -9+00 and -10+00).

Of the six storms which occurred between mid-September and mid-October, the largest occurred 10 days before the mid-October survey. A smaller storm occurred 3.5 days before the survey. Therefore, poststorm transport had at least some time to modify the 19 October storm profile. The pattern of profile change was reversed somewhat from that following the September storm. In general, the eroded disposal bar along the northeast ranges -3+00 and -4+00 was partially rebuilt and accretion occurred on the outer flank of the disposal bar for ranges -5+00 to -8+00. In addition, the bar extended even farther northeastward onto range -2+00, where it previously had not occurred. As before, no bar occurred on range -1+00. Some of the sand which partially filled the northeastward part of the trough following the September storm was eroded. The bar along the southwesternmost ranges -9+00 and -10+00 remained essentially unchanged, but the trough had filled in, resulting in a platform shape across the inshore zone.

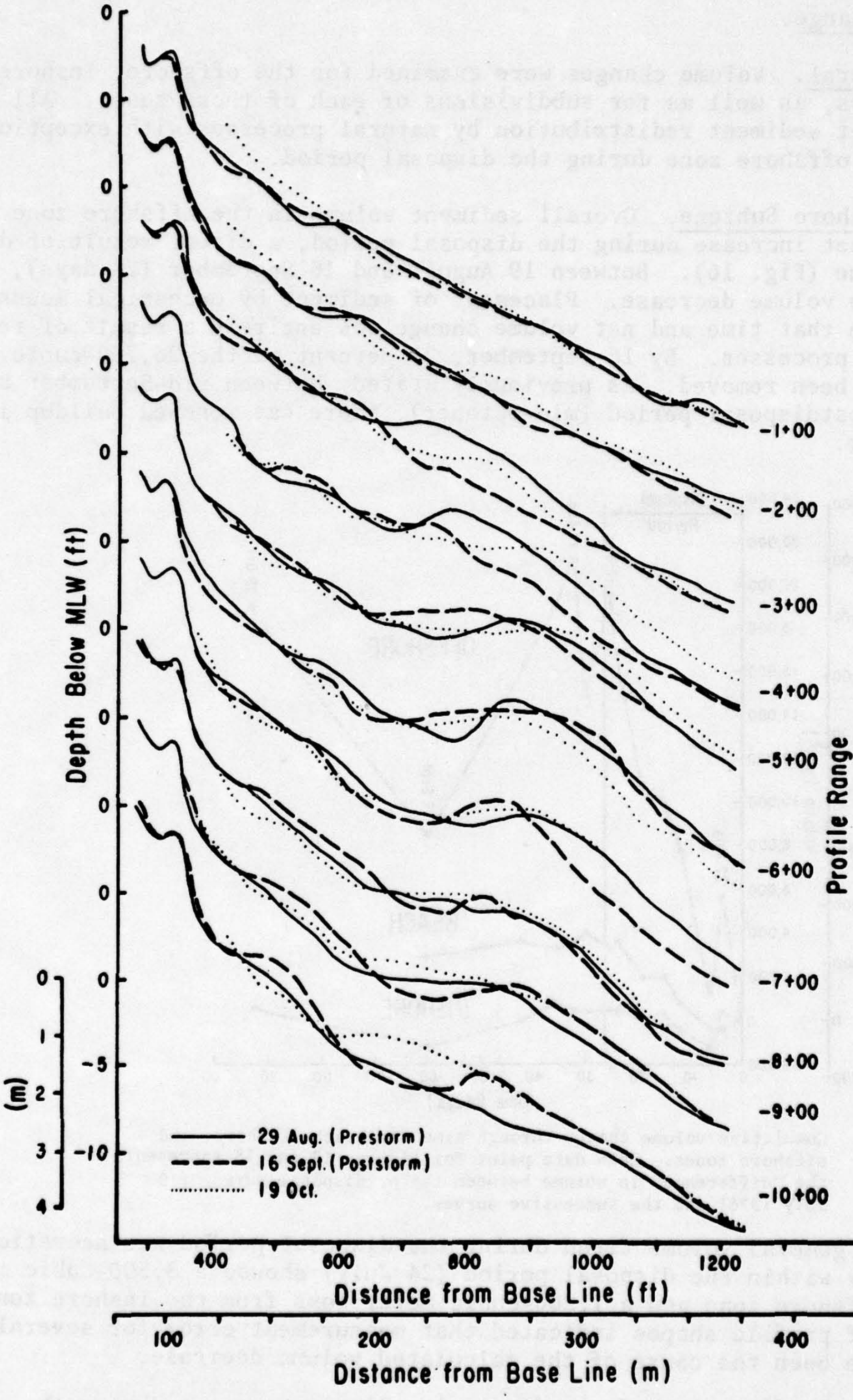

Figure 15. Time sequence of prestorm and poststorm profiles for all profile ranges.

c. Volume Change.

(1) General. Volume changes were examined for the offshore, inshore, and beach subzones, as well as for subdivisions of each of those zones. All volume trends reflect sediment redistribution by natural processes with exception of those for the offshore zone during the disposal period.

(2) Offshore Subzone. Overall sediment volume in the offshore zone showed a strong net increase during the disposal period, a direct result of disposal in that zone (Fig. 16). Between 19 August and 16 September (28 days), there was a large volume decrease. Placement of sediment by mechanical means had ceased before that time and net volume change was entirely a result of removal by natural processes. By 16 September, 75 percent of the 26,750-cubic meter excess had been removed. As previously stated, between mid-September and the end of the postdisposal period (mid-October), there was renewed buildup in the offshore zone.

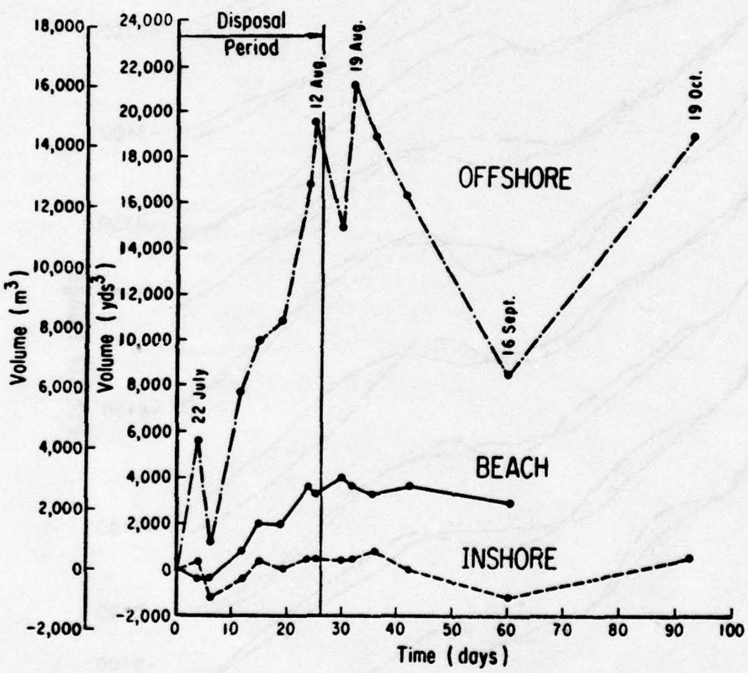

Figure 16. Cumulative volume change through time for beach, inshore, and offshore zones. Each data point for Figures 17 and 18 represents the "difference" in volume between the predisposal survey (19 July 1976) and the successive survey.

Although the general volume trend during the disposal period was accretion, the second survey within the disposal period (24 July) showed a 3,500-cubic meter loss from the offshore zone and a 1,200-cubic meter loss from the inshore zone. An examination of profile shapes indicated that measurement error for several profiles may have been the cause of the calculated volume decrease.

To determine the direction of net disposal sediment movement during the postdisposal period, the volume change for subdivisions of the offshore zone was examined. Volume change for the actual disposal zone (ranges -2+00 to -9+00) versus those of the flanking northeast offshore (-1+00 and -2+00) and southwest offshore (-9+00 and -10+00) zones are shown in Figure 17. The northeast offshore zone showed little overall change until after 16 September when slight accretion

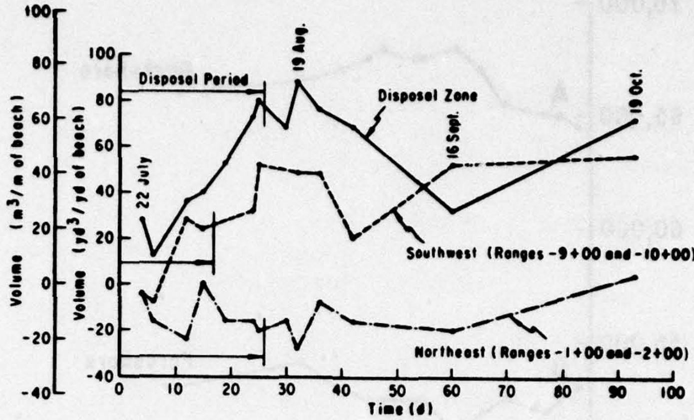

Figure 17. Volume change in the offshore zone for the disposal area and flanking northeast and southwest areas.

occurred (∿ 690 cubic meters). The time-sequence plots of individual profile ranges showed a negligible change along the northeastwardmost range (-1+00) with only a slight buildup along the adjacent range (-2+00) (Fig. 14; App. A).

The southwest offshore zone showed a greater volume increase than the up-coast zone (Fig. 17). This volume trend was partially a result of mechanical placement of disposal sediment slightly beyond range -9+00. However, natural buildup in this part of the offshore zone was also indicated by continued accretion during the postdisposal period. Although no sediment was mechanically placed along range -10+00, the southwestern limit of the study area, time-sequence profiles and area calculations for those profiles showed offshore accretion. The greater amount of offshore accretion in the southwest direction rather than the northeast direction corresponds with a predominance of waves and longshore currents toward the southwest during the postdisposal period.

The offshore disposal zone was also partitioned into 30-meter-wide shore-parallel subzones (Fig. 18, F to I). As in the case of volume change for the entire offshore zone (Fig. 16), all of the offshore subzones showed accretion during the disposal period (mechanically placed sand), and erosion during the first half of the postdisposal period and accretion in the second half of the postdisposal period (natural processes). In addition, following disposal and prior to the overall erosion trends, continued accretion occurred within some subzones. This accretion trend continued longer for the landward subzones than for the adjacent seaward subzones, resulting in a sequential offset of accretion peaks (maximums) in the volume trends for adjacent subzones (Fig. 18, F to H, time period 26 to 42 days). In general, the volume peaks shifted in the direction of increasing time for adjacent landward subzones indicating that a volume of sediment, or rather, the position of maximum buildup, migrated landward with time. Such a trend corresponds with onshore migration of the disposal bar form. The landwardmost subzone (Fig. 18F, 30 to 42 days) showed a longer duration of accretion than other subzones and was followed by a lower erosion rate.

(3) <u>Inshore</u>. Volume changes for the inshore zone were similar in trend to those of the offshore zone, but were of much lower magnitude and were totally a response to the natural redistribution of sand (Fig. 16).

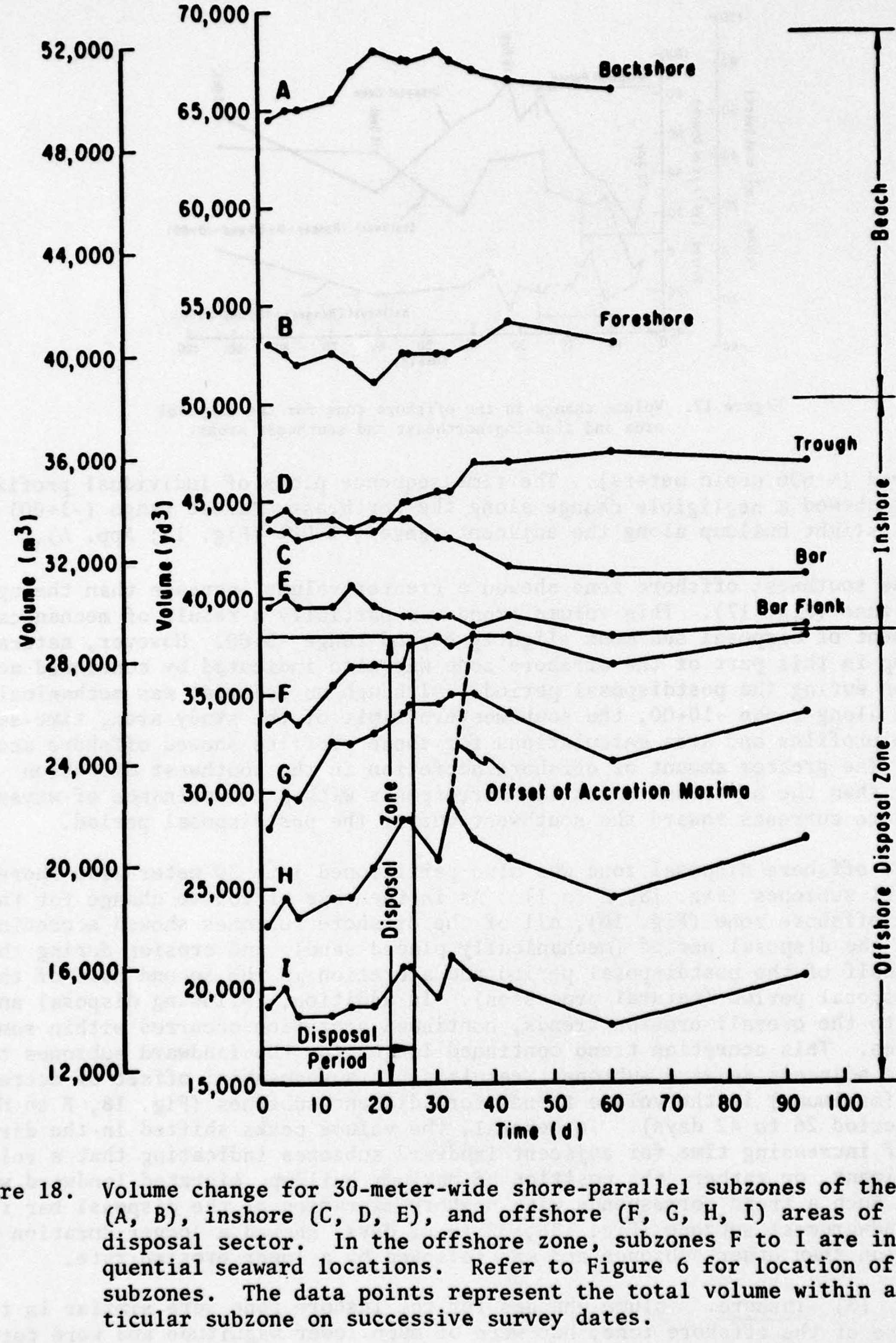

Figure 18. Volume change for 30-meter-wide shore-parallel subzones of the beach (A, B), inshore (C, D, E), and offshore (F, G, H, I) areas of the disposal sector. In the offshore zone, subzones F to I are in sequential seaward locations. Refer to Figure 6 for location of the subzones. The data points represent the total volume within a particular subzone on successive survey dates.

Following the initial volume decrease on 24 July, accretion occurred throughout the disposal period and continued into the early postdepositional period. Inshore accumulation at the end of that time was similar to the inshore volume just before the earlier erosion event. Following this accretion trend, erosion of the inshore ensued and continued until late in the postdisposal period, the loss being similar to the earlier amount of possible storm loss. By mid-October, inshore zone had again accreted.

The inshore zone contained the surf zone bar and trough. The time-sequence profiles show that these elements underwent significant modification following disposal. Volume changes were plotted for the three shore-parallel subzones comprising the inshore zone (Fig. 18, C, D, and E). These subzones correspond to the predisposal trough, surf zone bar, and bar flank position. Volume trends for the subzones reflect the shape modification of each profile element. The trough filled and the bar eroded at a high rate during the last of the disposal period and early postdisposal period. Later in the postdisposal period, volume change in the initial bar and trough positions were minimal and remained that way throughout the study period.

(4) Beach. The beach accreted during the disposal period to the early postdisposal period, then showed slight erosion. Overall, there was net accretion for the entire period of beach measurement. Volume change for subzones of the beach showed greater buildup in the backshore than the foreshore. Overall buildup of the backshore, including a slight volume decrease with time, corresponded to development and migration of the beach ridge. The net buildup of the foreshore subzone is related to infilling of the inner margin of the trough, which is included in that general subzone.

d. Textural Change. The predisposal profile was characterized by an overall textural trend in which sediment size decreased from coarse- and medium-sized sand on the beach, to fine-sized sand in the inshore zone, to fine- and very fine-sized sand in the offshore zone (Fig. 19). Three zones of local coarsening occurred within this overall trend. The zone of coarest material, with grain sizes ranging into the coarse sand class, was associated with the swash zone. The other two zones, showing only a slight coarsening, occurred in the surf zone trough and just seaward of the surf zone bar. In most locations, the sand was well sorted (Fig. 20). Poor sorting values were associated with the coarse sand in the swash zone.

Following sampling of the predisposal profile range -5+00, dredged sediment was placed in what was then the upcurrent direction (southwest), $\geq$ 15 meters from the sampled profile near profile range -6+00 (Fig. 19). No sediment was placed along the previously sampled native profile. The disposal sediment was coarser (composite Mn = 1.04 phi, 0.49 millimeter) and less well sorted (composite $S\phi$ = 1.02) than the native sand. The texture of the disposal sediment was most similar to the coarse, poorly sorted sediment of the swash zone.

Seven days following sediment disposal, profile -5+00 was resampled. A coarse textural anomally had developed across part of the earlier fine-grained inshore and offshore zones. This new coarse zone was characterized by fine- to coarse-grained, poorly sorted sand (Figs. 19 and 20, A-A'). Relatively large ripples ($\bar{L}$ = 25 centimeters, $\bar{H}$ = 5 centimeters), some asymmetric with steep sides landward, developed in the coarser zone replacing small-scale ripples ($\bar{L}$ = 5 centimeters, $\bar{H}$ = < 1 centimeter) of the previously fine-grained bottom. The

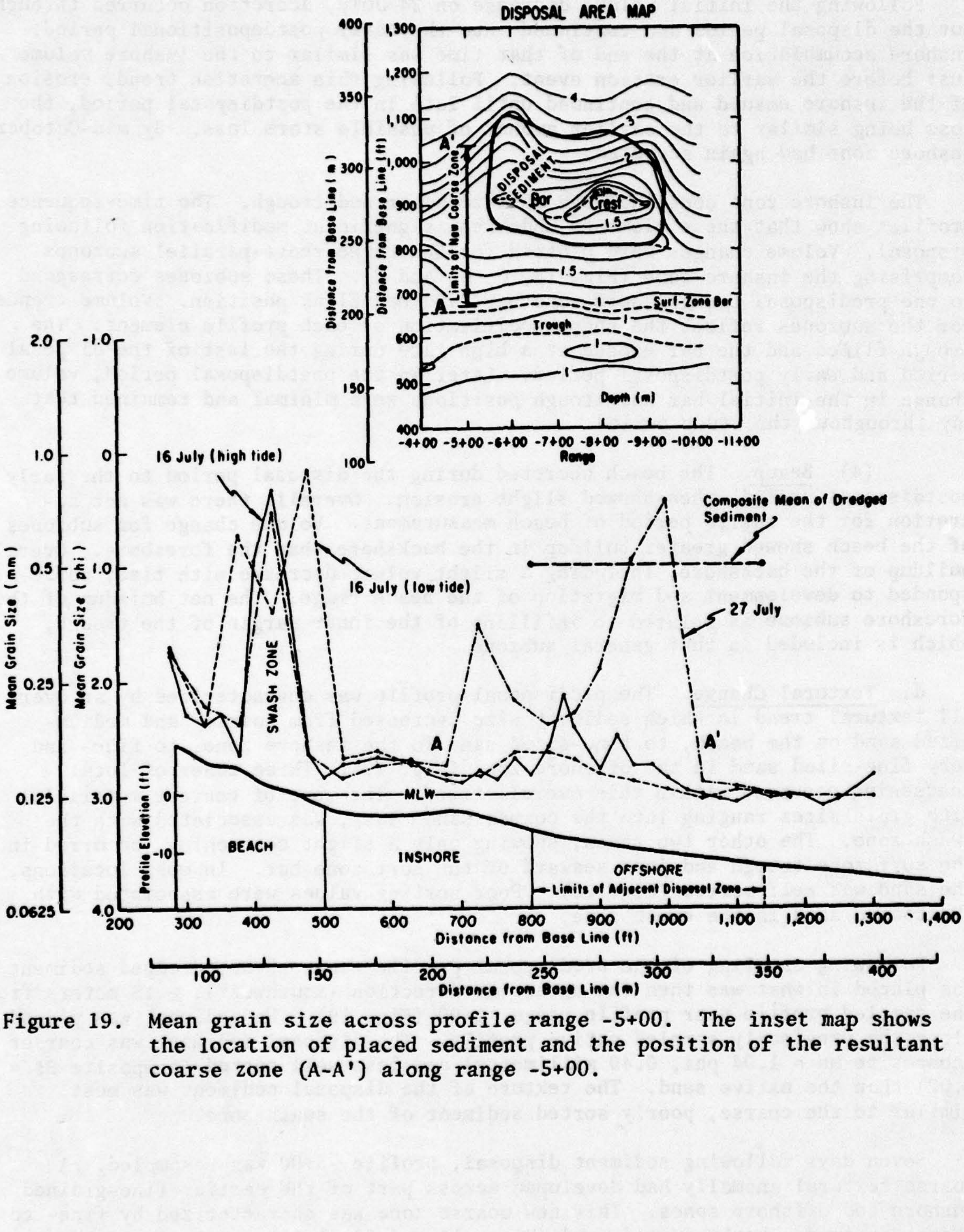

Figure 19. Mean grain size across profile range -5+00. The inset map shows the location of placed sediment and the position of the resultant coarse zone (A-A') along range -5+00.

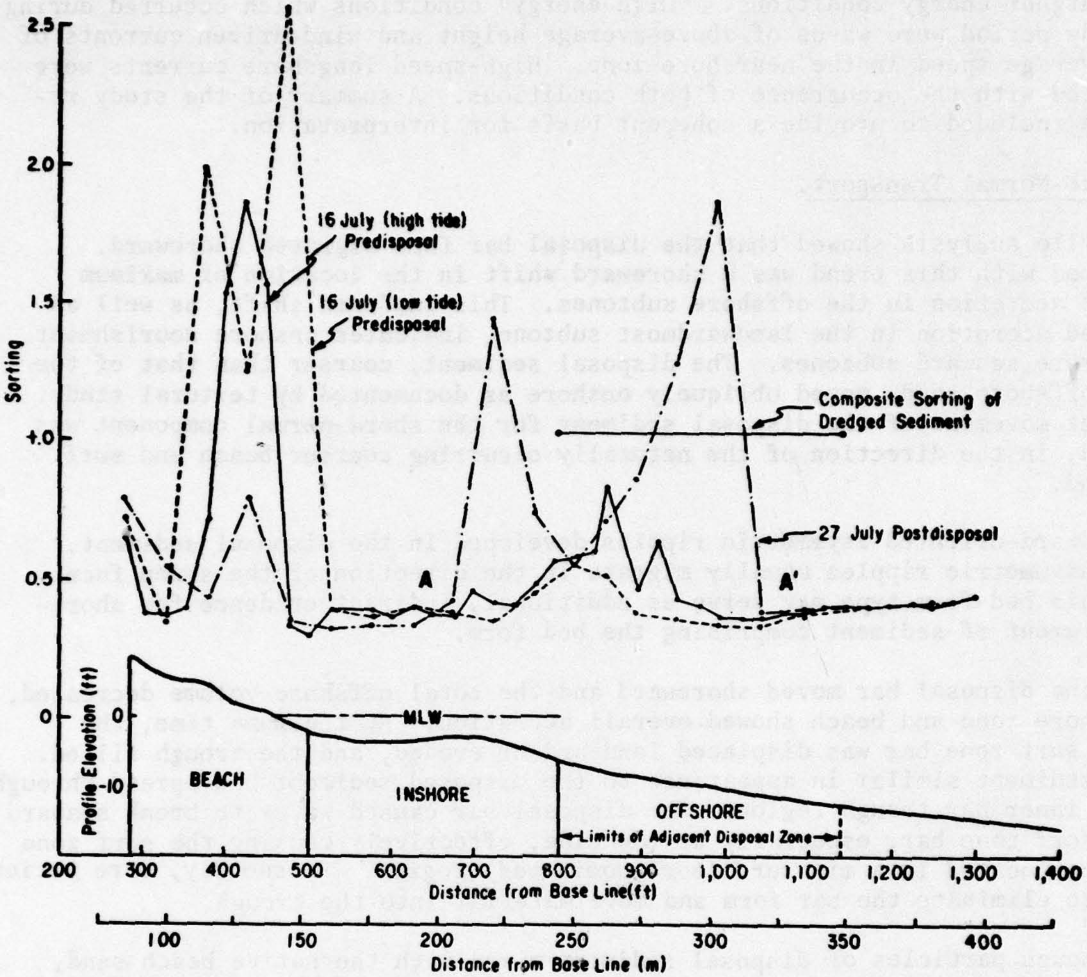

Figure 20. Sorting across profile range -5+00 (refer to Fig. 19 for the map location of A-A').

boundaries of the new coarse zone were located a minimum of 30 meters landward of the adjacent upcurrent disposed sediment indicating the disposal sediment had moved both onshore and alongshore.

Although no attempt was made to measure sediment texture for the beach and inshore zones through time, major textural changes were observed to occur in the trough and bar region. On some days, particularly following strong surf conditions, the trough became choked with coarse sediment identical in appearance to that of the disposed sediment. This coarse material occurred throughout the trough bar area and extended downcurrent far beyond the inshore zone of the study area.

V. DISCUSSION ON TRANSPORT OF DISPOSED SEDIMENT

1. General.

A synthesis of profile shape, volume, and textural data provides evidence for determining the primary transport direction of the disposal material. The shore-normal and shore-parallel components of net sediment movement represent the combined result of both fair-weather transport processes and transport

during higher energy conditions. "High-energy" conditions which occurred during the study period were waves of above-average height and wind-driven currents of above-average speed in the nearshore zone. High-speed longshore currents were associated with the occurrence of both conditions. A summary of the study results is included to provide a coherent basis for interpretation.

2. Shore-Normal Transport.

Profile analysis showed that the disposal bar form migrated shoreward. Associated with this trend was a shoreward shift in the location of maximum sediment accretion in the offshore subzones. This landward shift, as well as prolonged accretion in the landwardmost subzone, indicates onshore nourishment by the more seaward subzones. The disposal sediment, coarser than that of the native offshore sand, moved obliquely onshore as documented by textural study. Thus, net movement of the disposal sediment for the shore-normal component was landward, in the direction of the naturally occurring coarser beach and surf zone sand.

Landward-oriented asymmetric ripples developed in the disposal sediment. Active asymmetric ripples usually migrate in the direction of the steep face. Thus, this bed-form type may serve as additional, indirect evidence for shoreward movement of sediment comprising the bed form.

As the disposal bar moved shoreward and the total offshore volume decreased, the inshore zone and beach showed overall accretion. At the same time, the natural surf zone bar was displaced landward or eroded, and the trough filled. Coarse sediment similar in appearance to the disposed sediment had spread throughout the inner bar trough region. The disposal bar caused waves to break seaward of the surf zone bar, especially at low tide, effectively causing the surf zone bar to be located in a mid-surf (bore-dominated) region. Presumably, bore action tended to eliminate the bar form and move material into the trough.

Although particles of disposal sediment mixed with the native beach sand, net accretion on the beach was slight. The beach ridge, which began to develop before disposal and eventually welded onto the backshore throughout the study period, was related to a natural cycle of beach change (Hayes, 1977).

There was no evidence for seaward displacement of the disposal bar. Following the major storm on 16 September, the beach, inshore, and offshore zones did, however, undergo temporary erosion. Although some of this loss is presumed to have been seaward, evidence indicates a major amount of longshore transport (see Section V,4).

3. Shore-Parallel Transport.

The inshore zone northeast and southwest of the disposal sector experienced a high rate of trough filling. Longshore currents were observed to move much of the sediment along the entire inshore zone. Several times the coarse sediment filling the inshore zone of the sector was traced in the direction of the longshore current, and beyond the limits of the study area.

It is difficult to assess the amount of shore-parallel movement of disposal sediment out of the offshore disposal area into adjacent offshore areas. Placement of a sediment pile in the nearshore should create a local disequilibrium,

which, if shore-parallel transport of that material were highly effective, might lead to a downcurrent buildup. Intermittent coastal currents, e.g., wind-driven currents, were capable of transporting sediment alongshore. An alongshore buildup of disposal material occurred in those profiles directly adjacent to the disposal area. The lateral movement of the more seaward material is interpreted, though, to be primarily a result of storm-generated transport along the bar axis. Also, it is likely that sediment moving alongshore, but seaward of the bar, would not move in the form of a large, discrete bed form, but rather as discrete particles comprising an unnoticeable, sheetlike layer. Nonetheless, the relatively small volume of shore-parallel accretion in the adjacent offshore zone, and the timelag between inshore filling of the surf zone and alongshore buildup in the offshore zone, suggest that shore-parallel transport of disposal sediment was much greater in the surf-dominated inshore zone than in the adjacent seaward offshore zone. This is supported by the fact that diver observation and current meter data showed the shore-parallel component of flow for the surf zone to consistently exceed that of shore-parallel flow seaward of the surf zone.

4. Storm Effects.

Storm-induced currents of the 16 September storm had the effect of transporting disposal sediment onshore and alongshore to cause erosion at the upcurrent end of the disposal bar, and lateral bar growth at its downcurrent end. Some sediment may have been transported offshore, but a more seaward storm bar or a noticeably built-up bottom was not observed. It is likely that most of the sediment filling the northeast (upcurrent) end of the trough came from the adjacent eroded bar in response to wave and longshore transport. Downcurrent, where the disposal trough was not filled, well-developed troughs were cut into the *disposal platform or deeper* into an already developed disposal trough. However, sediment at these locations also accreted to the inshore margin, perhaps in response to landward sediment transfer across the upcurrent trough and in response to shielding from storm wave erosion by the disposal bar.

The disposal bar, thus, acted in part as a storm bar during the increased energy conditions. During fairer weather conditions, disposal sediment tended to move landward and ultimately develop a platform. Presumably, depending on breaker type (i.e., plunging versus spilling), breakpoint location, and longshore current velocity, a trough was maintained.

Evidence indicates that the overall bulk of net sediment displacement occurred in the inshore and shallowest part of the offshore subzones, particularly along the bar and trough complex. This is in accord with the findings of recent transport studies conducted by Kamphuis and Readshaw (J.W. Kamphuis, Queen's Uinversity, Kingston, Ontario, personal communication, 1978). Using a three-dimensional, coastal basin model, they found that for the simulated summer wave cycle (minor storm conditions) onshore transport prevailed until sediment reached the inshore zone. Then, predominant transport became longshore. For a barred profile, in which the bar was a storm bar, most of the sediment transport during fair-weather conditions occurred landward of the bar in the swash and surf zones. During storm conditions in which waves broke upon the seaward bar, the zone of maximum transport was predominantly shore-parallel along the bar crest with essentially no effect on the beach.

By mid-October, shore-parallel transport from the southwest had been sufficient to cause a renewed lateral growth of the bar toward the northeast. In

addition, with the predominant wave direction during this time period being from the east (northeastward of shore normal), it is not unreasonable to assume that the bar also extended farther to the southwest, beyond the limits of the study area. The trough-filling and platform development on the southwest end may have resulted from transport from the southwest, in a manner similar to that of the northeast September storm, or perhaps from net downcurrent accumulation from northeasterly currents and bar-shielding of easterly waves.

Accretion on the outer flank of the disposal bar and shore-parallel rebuilding of the bar between mid-September and mid-October are of special importance to the general concept of sediment redistribution as a response to storm transport. Sediment redistribution in this case resulted in a volume increase in the inshore and offshore zones. Profile shapes indicate little evidence for erosion of the beach and inner profile with sediment transfer to the outer profile. Sediment simply seems to have been added to the inshore zone and innermost part of the offshore zone. This suggests that storm levels were not sufficient to cause much seaward displacement of sediment from the inner profile, or that if seaward displacement did occur, poststorm recovery was extremely rapid. High poststorm recovery rates for transport from the offshore to the inshore are not supported, though, by other profile studies (Nordstrom and Inman, 1975). Thus, it is likely the source of the added sediment may have been from some alongshore location or from within the offshore region. During storms, the disposal bar acted as a storm bar, promoting longshore transport and lateral extension of the bar itself.

5. Wind- and Wave-Driven Longshore Currents.

Wind may have a significant effect on moving sediment in the coastal zone, both outside and within the surf zone. It is generally acknowledged that the wave-driven longshore current is often modified by other currents in the nearshore system, e.g., wind-driven and tidal currents (Komar, 1976a, p. 198). Depending on whether the wave-driven longshore current and wind-driven current are in the same or opposite directions, a higher or lower speed resultant longshore flow should ensue.

Longshore current speed correlates with breaker height and angle of wave breaking (Bowen, 1969; Longuet-Higgins, 1970; Thornton, 1971) as well as with other variables (Komar, 1976a). The LEO data for this study site show that although relatively higher velocity longshore currents (e.g., > 30 centimeters per second) sometimes occurred in association with high waves and lower angles of wave breaking, there was not always a positive association between current velocity and observed breaker conditions (viz, height, period, and angle of breaking) (Fig. 10). In fact, many of the longshore current speeds > 30 centimeters per second were associated with relatively low breaker heights ($\leq$ 0.6 meter). In most cases, the occurrence of higher speeds, especially those during nonstorm conditions, was apparently associated with the development of a local sea with wind and wave directions at a low angle to the coast. Maximum longshore speeds developed in conjunction with a sustained local sea, but not necessarily large breaker conditions, or developed during a storm when winds produced large waves breaking at a low angle, e.g., the northeaster of 14 to 16 September. Similarly, Galvin and Nelson (1967) reported that from a compilation of 352 longshore current observations, the highest longshore current speeds were wind-aided. Thus, local seas and associated wind-driven currents appear to be instrumental in producing higher velocity longshore current speeds, and therefore

producing higher transport rates, than would be expected for the observed breaker heights and angles.

The conditions necessary to produce wind-driven currents were observed to occur rather frequently throughout the study period. Based on the dye study on 21 July, it is reasonable to assume that the wind-driven current extended landward into the surf zone (Fig. 4). Moreover, a shore-parallel wind-driven current was measured to extend downward near the bed of the nearshore zone (Fig. 12). Thus, these currents are judged not to be simply a surface current.

In general, a superimposed net flow of any speed, e.g., a few centimeters per second, is sufficient to cause net displacement of a sand grain already entrained by orbital currents. Therefore, the measured current would definitely have been capable of moving wave-entrained sediment shore parallel throughout the nearshore zone. When the velocity exceeded 20 centimeters per second, sediment may have been entrained by the wind-driven current alone.

Inspite of the capability of wind-driven currents to move sand, the profile data of this study are not suitable for examining shape and volume change in relation to known periods of wind-driven current activity. Nonetheless, wind-driven currents were probably instrumental in moving larger-than-expected amounts of sediment in a shore-parallel direction both in the surf zone and in the adjacent offshore zone.

6. Overall Transport Pattern and Rate.

The predominant transport pattern for the disposal sediment was movement onshore, into the inshore and beach zones, then alongshore. This pattern is in accord with field-measured dispersal patterns for fine- to medium-grained radioactive sand tracers placed in the California nearshore zone (Duane, 1976; Schwartz, 1976, 1980 in preparation) as well as with dispersal patterns for fluorescent tracer studies (Ingle, 1966). The radioactive tracer tests showed that sediment which entered the inshore zone tended to remain in that zone unless moved seaward by rip current (Schwartz, 1976).

This general pattern is also in accord with laboratory studies in which sand was placed in shallow water just seaward of the surf zone (Kamphuis and Bridgeman, 1975). The wave tank study by Kamphuis and Bridgeman (1975) showed that placed sediment moved shoreward and accreted to the lower beach and inshore zone in response to simulated summer wave (minor storm) conditions. More recently, a similar nourishment study conducted in a wave basin by Kamphuis and Readshaw (J.W. Kamphuis, personal communication, 1978) showed the major difference in the processes for the two- and three-dimensional settings was the generation of a longshore current in the wave basin. Under similar sediment placement and wave conditions, the sediment again moved shoreward, but once in the region of longshore currents, transport became dominantly shore parallel. This resulted in beach accretion downcoast from the fill location rather than directly onshore. Although similar accretion has not been documented for this study, the comparison of field studies and laboratory studies provides evidence for onshore transport into the littoral zone where longshore transport then becomes dominant. Thus, sediment may be supplied to the surf zone at a relatively high rate and also moved alongshore at a high rate.

Six days following final disposal, 40 percent of the placed 26,750 cubic meters of sediment had been removed from the offshore zone, 55 percent removed

16 days after disposal, and 75 percent removed 34 days after disposal ceased. This is an average loss rate of approximately 340 cubic meters per day from the offshore zone. As previously stated, evidence indicates that most of the volume lost from the offshore zone had moved shoreward. The beach zone, including the accreted ridge material, showed a 10-percent gain 6 days after disposal ceased but had decreased by 2 percent 34 days later for a final 8-percent net gain. The inshore zone initially showed a 1.5-percent gain, 6 days after disposal, followed by a slight volume decrease. Thus, net accretion on the beach slightly exceeded that in the inshore zone. The sum of net accretion for both zones does not balance the amount of offshore loss, indicating a loss from the system.

Movement from the disposal reach was highest in the longshore direction out of the inshore zone. Tracer data from a California study of the nearshore zone show that longshore transport rates are highest for what would correspond to the inshore zone of this study area, next highest for the beach zone, and lowest for the offshore zone (Duane, 1970). Thus, although the total amount of inshore accretion in this study was low, transport through that zone was probably high.

Profile data show that although there was little overall change in the shape or volume of the foreshore, accretion did occur farther landward on the backshore and seaward in the inshore trough. Some of the beach accretion was due to a natural cycle of beach-ridge formation. Once sediment moves landward beyond the foreshore, the probability of entrainment and removal from the backshore is much reduced. A longer residence time is thus expected for particles moved onto the beach than for those moved into the inshore zone. This explains the greater net volume gain for the beach versus the inshore in the study area, even though it is known that a much greater volume of disposal sediment entered and moved through the inshore zone.

VI. CONCLUSIONS

The results of this experiment are encouraging with respect to the concept of sand bypassing and beach nourishment using a split-hull type barge. Dredged sediment, similar in grain size to that of the native beach, was placed in a zone between the original 2- and 4-meter depth contours and was moved, by waves, landward into the innermost part of the littoral zone. However, a relatively small part of the total amount placed offshore was accounted for in the surveyed beach and inshore zones. The longshore current was of major importance in moving the disposal material once it reached the surf zone. Instead of moving directly shoreward onto the beach, much of the sand was deflected and eventually moved in a longshore direction, feeding the adjacent littoral zone and beach areas.

Disposal piles were modified soon after placement to form a bar which eventually migrated landward. The bar relief and the volume of sediment contained in the bar decreased during its landward migration. By the time the bar reached the surf zone its shape was lost or greatly diminished.

At the same time the disposal bar was built and began to migrate onshore, the natural surf zone bar, located landward of the disposal area, began to erode and also move landward. Eventually, the surf zone bar was eliminated and its associated trough filled. This trough filling does not just reflect bar displacement. Sediment from the offshore also moved landward into the inshore zone and then longshore. This pattern is supported by the combined set of volume and textural data as well as what appeared to be simple filling of the trough away from the immediate disposal area.

With landward migration of the disposal bar, removal of the surf zone bar, and filling of the inshore trough, a platform was created which widened the surf zone. In some cases, a new trough was cut in this platform at the old surf zone bar position. The development of such a platform may provide additional beach protection benefits by increasing wave energy dissipation in the surf zone. Wave refraction around the disposal zone may also promote sediment accretion landward of the zone, as in the case of offshore breakwaters; however, because of the rapid removal of the disposal piles, this is only a short-term gain.

Bottom changes for a distance of 60 meters seaward of the disposal site were evaluated from the survey coverage. In a single case, between 16 September and 19 October, a period during which a number of minor to moderate coastal storms occurred, the offshore area gained sediment. The offshore buildup is interpreted to reflect shoreward accretion onto the disposal bar as well as longshore extension of the disposal bar. The seaward-displaced depth contours of the new profile caused by the presence of the placed disposal material, appeared to have promoted onshore transport.

The disposal bar apparently served as a storm bar. Evidence indicates that in response to the mid-September storm, major transport was shore parallel along the bar axis and that sediment accreted on the landward flank of the bar and inshore of the trough.

The occurrence of shore-parallel, wind-driven currents capable of transporting sediment throughout the nearshore zone was documented. Wind-driven currents apparently occur quite frequently, and, if flow is in the same direction as a swell-induced longshore current, the resultant transport in the surf zone may be higher than expected. It was not possible to judge the effect of wind-driven currents on the disposal sediment other than to acknowledge shore-parallel transport out of the disposal area both seaward of and within the surf zone in response to such currents.

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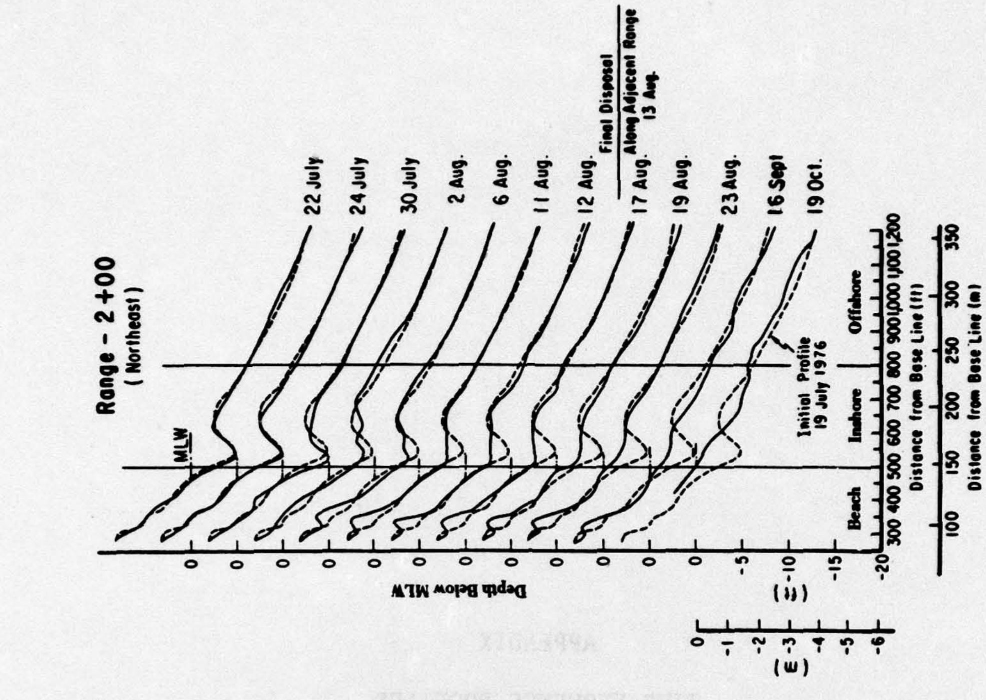
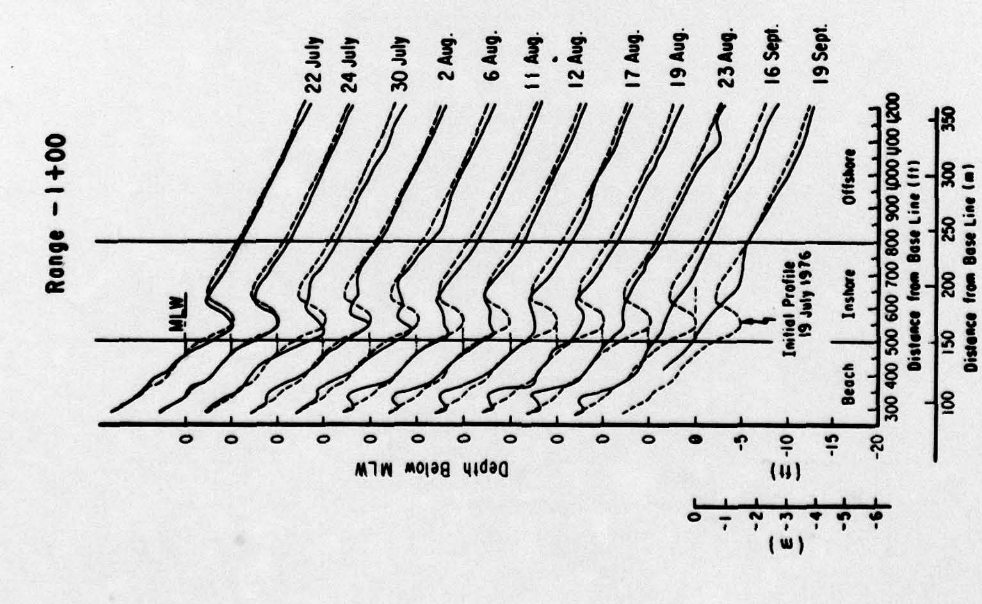
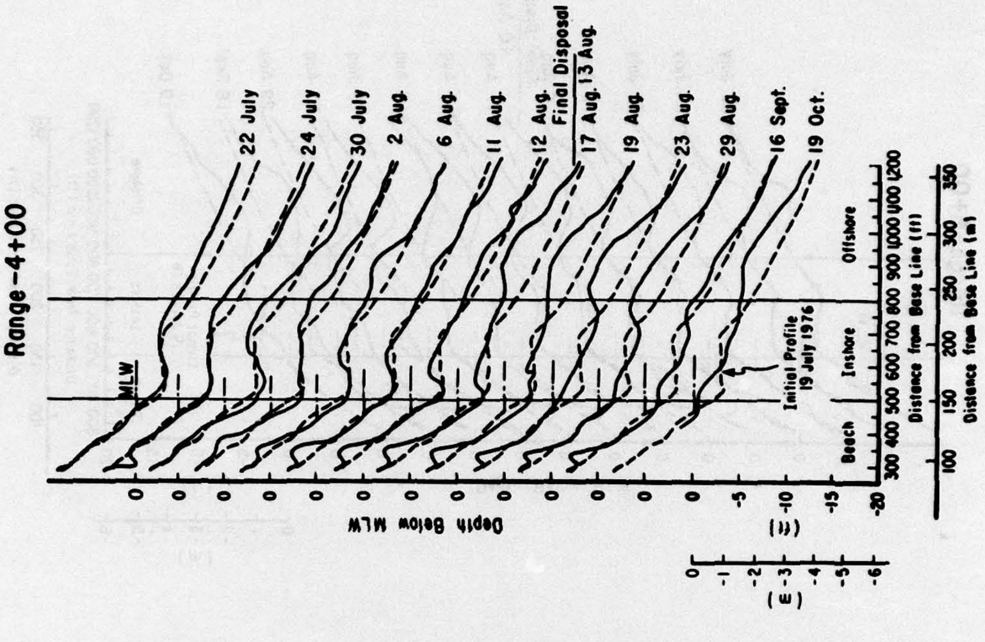
APPENDIX

TIME-SEQUENCE PROFILES

This appendix contains time-sequence profiles for all survey ranges. Each profile sequence is referenced to a predisposal survey.


Range - 2+00
(Northeast)
MLW
Depth Below MLW
(ft)
(m)
22 July
24 July
30 July
2 Aug.
6 Aug.
11 Aug.
12 Aug.
Final Disposal Along Adjacent Range 13 Aug.
17 Aug.
19 Aug.
23 Aug.
16 Sept
19 Oct.
Initial Profile 19 July 1976
Beach
Inshore
Offshore
Distance from Base Line (ft)
Distance from Base Line (m)


Range - 1+00
MLW
Depth Below MLW
(ft)
(m)
22 July
24 July
30 July
2 Aug.
6 Aug.
11 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
16 Sept.
19 Sept.
Initial Profile 19 July 1976
Beach
Inshore
Offshore
Distance from Base Line (ft)
Distance from Base Line (m)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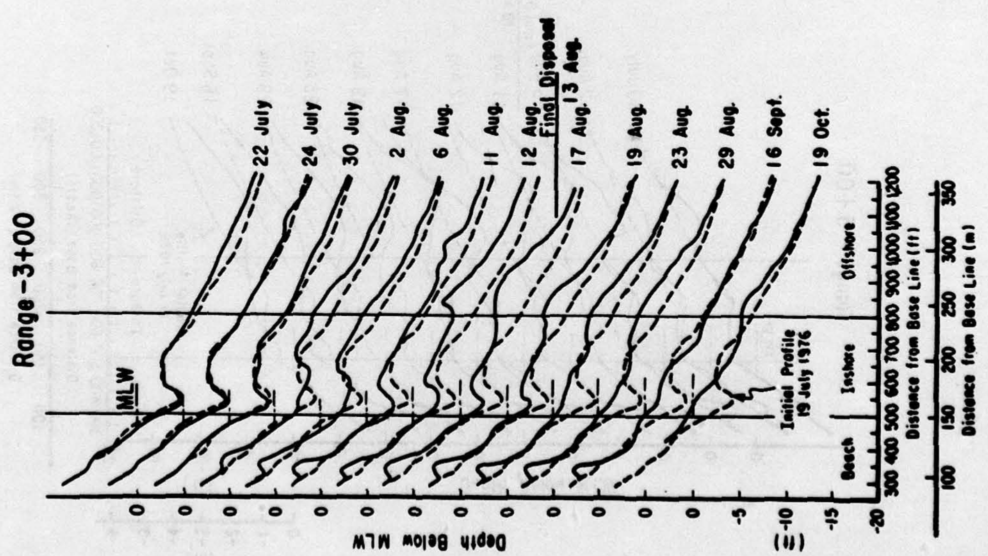
MLW
22 July
24 July
30 July
2 Aug.
6 Aug.
11 Aug.
12 Aug.
Final Disposal
13 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Depth Below MLW
(ft)
(m)
300 400 500 600 700 800 900 1000 1100 1200
Distance from Base Line (ft)
100 150 200 250 300 350
Distance from Base Line (m)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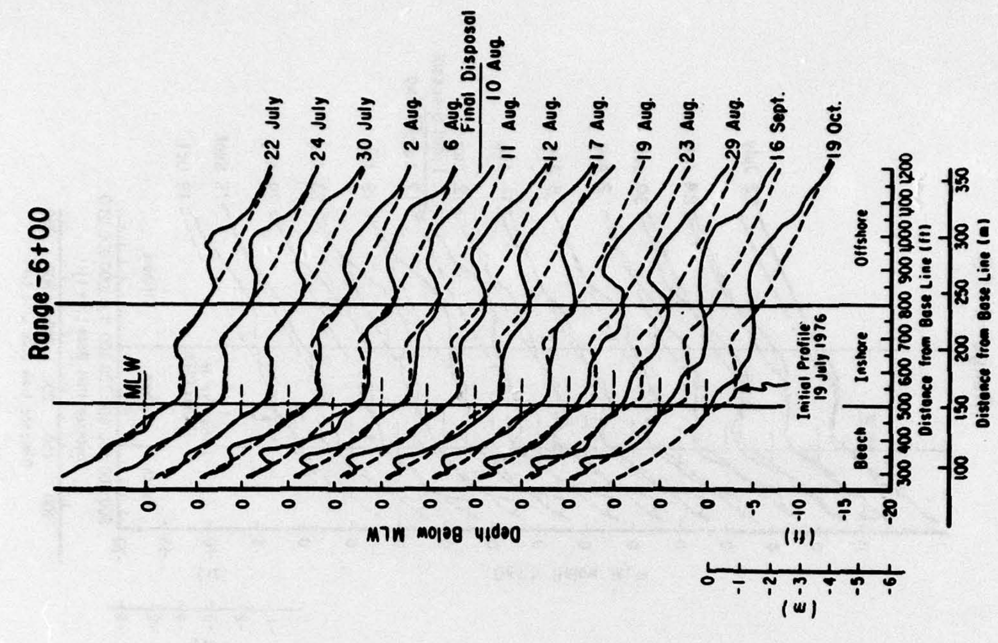
MLW
22 July
24 July
30 July
2 Aug.
6 Aug.
11 Aug.
12 Aug.
Final Disposal
13 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Depth Below MLW
(ft)
(m)
300 400 500 600 700 800 900 1000 1100 1200
Distance from Base Line (ft)
100 150 200 250 300 350
Distance from Base Line (m)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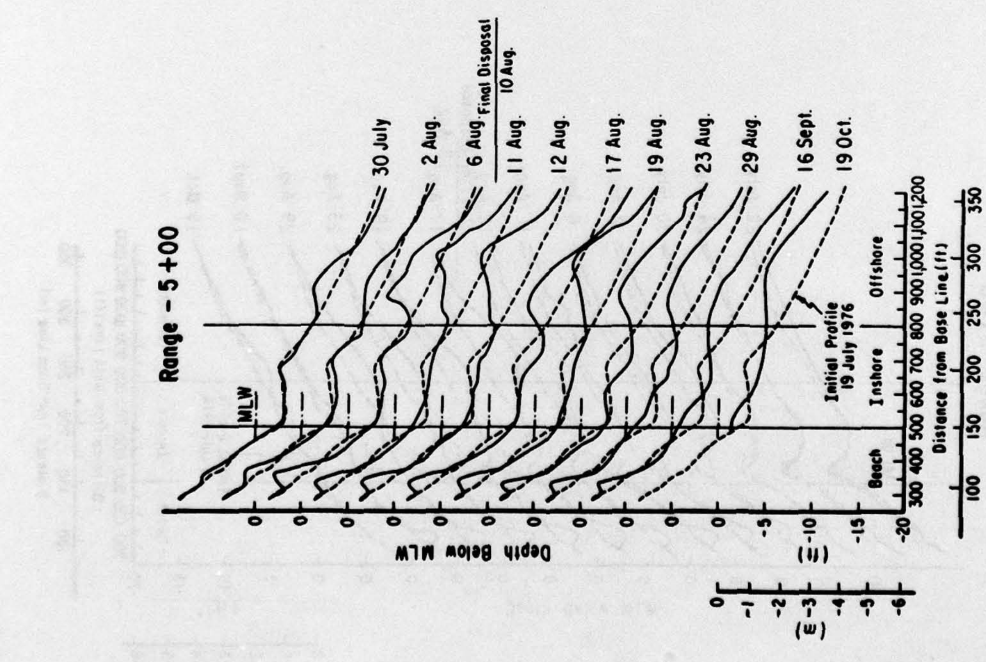
MLW
22 July
24 July
30 July
2 Aug.
6 Aug.
Final Disposal
10 Aug.
11 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Depth Below MLW
(ft)
(m)
Distance from Base Line (ft)
Distance from Base Line (m)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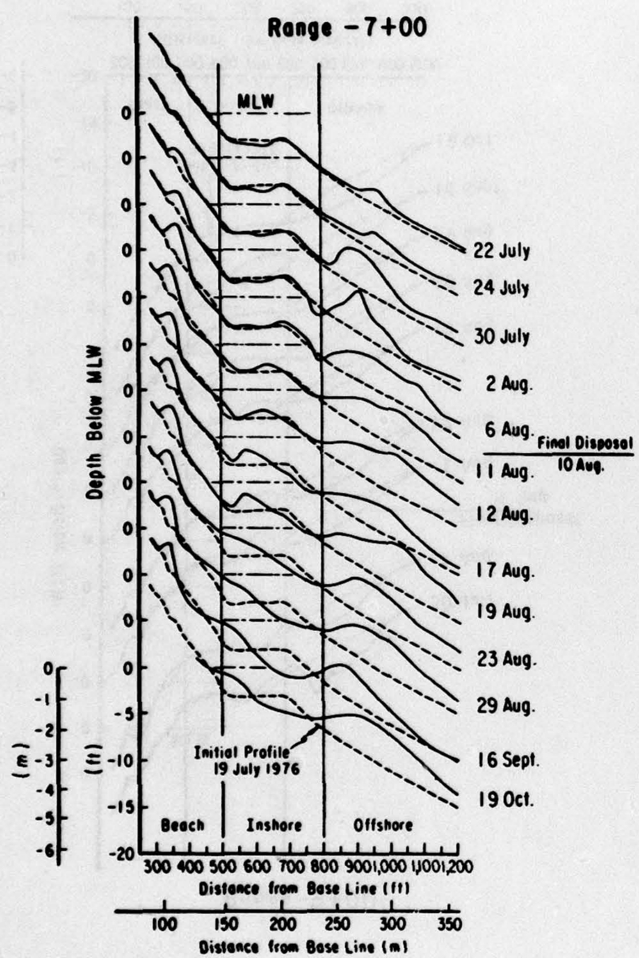
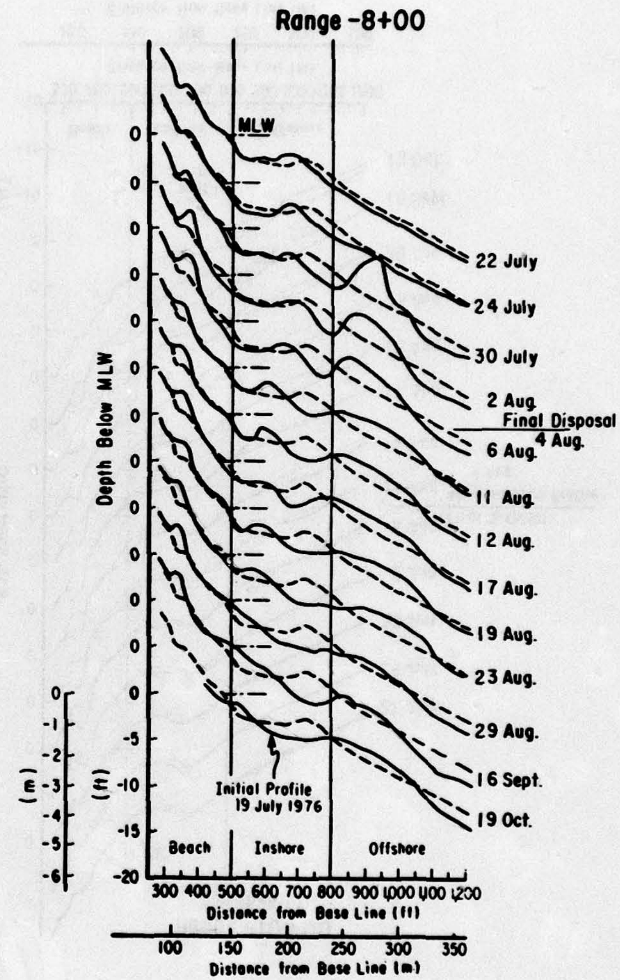
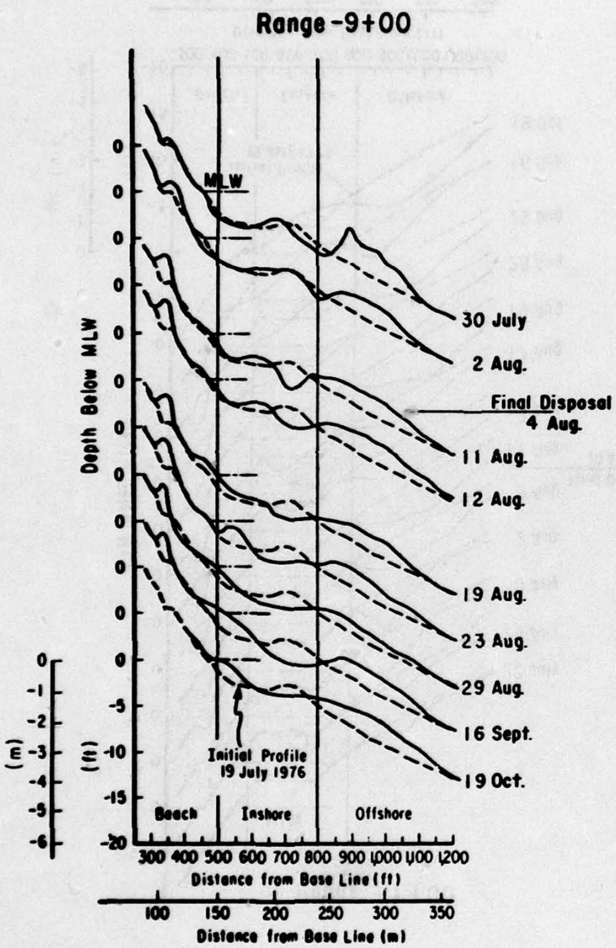
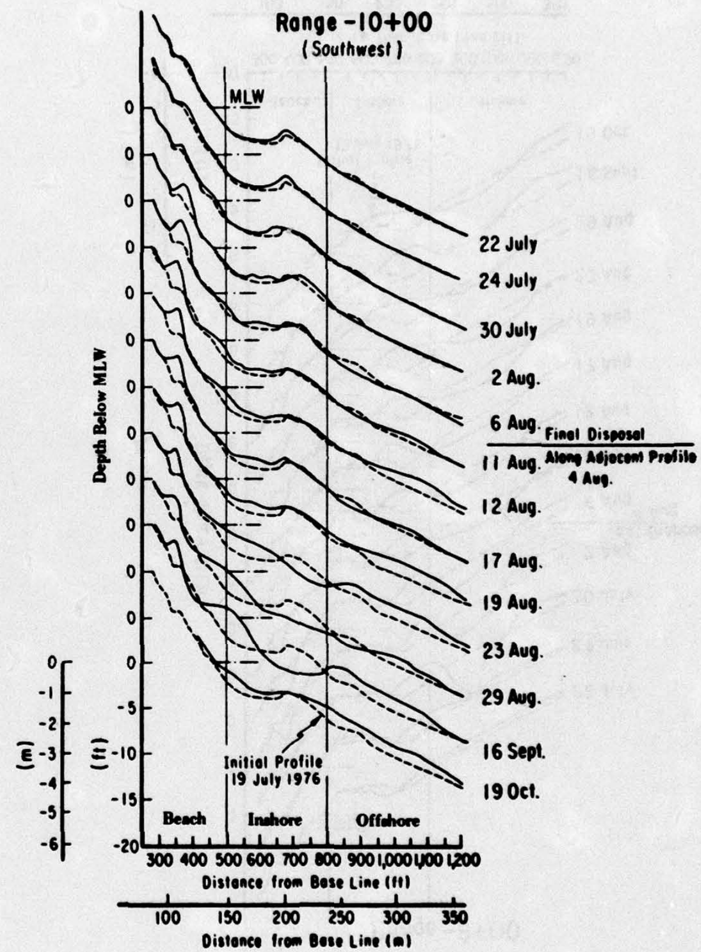
MLW
30 July
2 Aug.
6 Aug.
Final Disposal
10 Aug.
11 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Depth Below MLW
(ft)
(m)
Distance from Base Line (ft)
Distance from Base Line (m)


Range -7+00
MLW
Depth Below MLW
(ft)
(m)
Beach
Inshore
Offshore
Initial Profile
19 July 1976
22 July
24 July
30 July
2 Aug.
6 Aug.
Final Disposal
10 Aug.
11 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
300 400 500 600 700 800 900 1,000 1,100 1,200
Distance from Base Line (ft)
100 150 200 250 300 350
Distance from Base Line (m)


Range -8+00
MLW
Depth Below MLW
(ft)
(m)
Beach
Inshore
Offshore
Initial Profile
19 July 1976
22 July
24 July
30 July
2 Aug.
Final Disposal
4 Aug.
6 Aug.
11 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
300 400 500 600 700 800 900 1,000 1,100 1,200
Distance from Base Line (ft)
100 150 200 250 300 350
Distance from Base Line (m)


Range -9+00
MLW
Depth Below MLW
(ft)
(m)
30 July
2 Aug.
Final Disposal
4 Aug.
11 Aug.
12 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Distance from Base Line (ft)
Distance from Base Line (m)


Range -10+00
(Southwest)
MLW
Depth Below MLW
(ft)
(m)
22 July
24 July
30 July
2 Aug.
6 Aug.
Final Disposal
11 Aug.
Along Adjacent Profile
4 Aug.
12 Aug.
17 Aug.
19 Aug.
23 Aug.
29 Aug.
16 Sept.
19 Oct.
Initial Profile
19 July 1976
Beach
Inshore
Offshore
Distance from Base Line (ft)
Distance from Base Line (m)

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TC203 .U581tp no. 80-1 627

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